LimitState:SLAB Manual

VERSION 2.3.1

LimitState Ltd

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LimitState Ltd
The Innovation Centre
217 Portobello
Sheffield S1 4DP
United Kingdom
T: +44 (0) 114 224 2240
E: info@limitstate.com
W: limitstate.com

LimitState:SLAB 2.3.1

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This document is provided as a guide to the use of the software. It is not a substitute for standard references or engineering knowledge. The user is assumed to be conversant with standard engineering terminology and codes of practice. It is the responsibility of the user to validate the software for the applications for which it is to be used.

Contents

Part I

Introduction and Quick Start

Chapter 1

Introduction

1.1 About LimitState

LimitState Ltd was spun out from the University of Sheffield in 2006 to develop and market cutting edge ultimate analysis and design software for engineering professionals. LimitState:SLAB is one of a number of LimitState products, with applications in the structural, geotechnical and mechanical engineering sectors. We aim to be a world leading supplier of computational limit analysis and design software. LimitState maintains close links with the University of Sheffield, enabling us to draw on and rapidly implement the latest innovations in numerical and theoretical limit state analysis.

1.2 General Overview

1.2.1 LimitState:SLAB

LimitState:SLAB is a software program designed to rapidly evaluate the load carrying capacity of existing and proposed concrete slab structures using the yield-line analysis method.

Unlike many other analysis methods and tools, LimitState:SLAB uses modern optimization techniques to identify the most critical layout of yield-lines for the defined problem, removing the need to propose a potential failure mechanism at the outset or manually refine the mechanism until an acceptable (and arbitrary) degree of accuracy is achieved.

LimitState:SLAB can be used to model problems of any geometry specified by the user, including those containing columns, walls and holes.

The software directly determines the ultimate limit state (ULS) collapse conditions using Discontinuity Layout Optimization (DLO) (see Chapter II), and is designed to work with modern engineering design codes by providing full support for partial factors and the ability to solve multiple load cases.

1.2.2 The Yield-line Method

The yield-line method is a robust and powerful technique for estimating the ultimate capacity of concrete slabs. It is simple to understand, but also possesses the versatility to address a wide range of problem types. The method traditionally involves postulating a failure mechanism (or yield-line pattern) and then using work or equilibrium equations to calculate the loading required to cause collapse.

The method has a number of benefits, both when designing and assessing slab structures. For cases of designing slabs, Kennedy & Goodchild (2004) identified the following when reviewing the technique for a Concrete Centre design guide:

> ”Yield Line Design has the advantages of:
>
> 1. Economy
> 2. Simplicity
> 3. Versatility
>
> Yield Line Design leads to slabs that are quick and easy to design, and are quick and easy to construct. [...]
>
> The resulting slabs are thin and have very low amounts of reinforcement in very regular arrangements. The reinforcement is therefore easy to detail and easy to fix and the slabs are very quick to construct.
>
> Above all, Yield Line Design generates very economic concrete slabs, because it considers features at the ultimate limit state. [...]”

It naturally follows that, for the assessment of existing slab structures, the Yield-Line method will be able to highlight inherent strength in slabs that may not have been considered during the design stage. This makes it an ideal tool when repurposing a building with contents that surpass the initial design loading.

However, Kennedy & Goodchild (2004) note that:

> ”...a traditional and legitimate concern has been that an overestimate of the true capacity will be obtained unless the correct collapse mechanism has been identified.”

An automated method capable of reliably and systematically identifying critical yield-line patterns, as highlighted above, has long been sought and various methods have previously been put forward (e.g. Munro & Da Fonseca 1978, Johnson 1994, etc.). However, none of these methods have been sufficiently capable enough to find widespread application in engineering practice.

LimitState:SLAB solves these problems by using state-of-the-art optimization techniques (DLO) to identify, for any particular problem, the critical layout of yield-lines and therefore provide a very close upper bound on the true solution.

1.2.3 Discontinuity Layout Optimization

The ‘Discontinuity Layout Optimization’ (DLO) procedure (originally introduced in Smith & Gilbert 2007) provides a simple yet systematic and completely general means of identifying critical collapse mechanisms in plastic analysis problems. LimitState:SLAB harnesses the power of this procedure in a simple-to-use yet powerful software product. The application of DLO to yield-line analysis is outlined in Gilbert et al. 2014.

More information about the DLO procedure is also given in Chapter II

1.3 Program Features

LimitState:SLAB is designed to be general, fast and easy to use. The main features of LimitState:SLAB are summarized below:

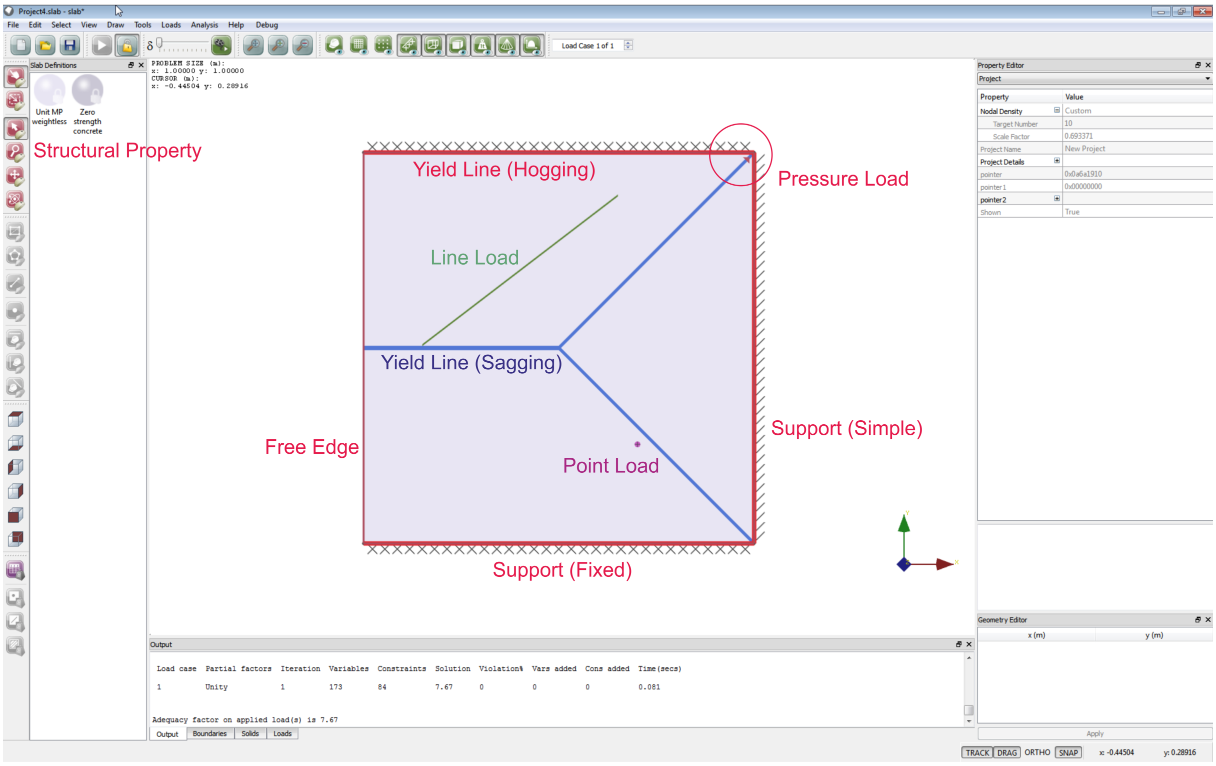
- LimitState:SLAB utilizes Discontinuity Layout Optimization (DLO) to directly identify the critical yield-line collapse mechanism. The DLO procedure effectively relies on the familiar ‘mechanism’ method of analysis originally pioneered for slabs by workers such as Johansen (1962), but posed in a modified form to allow modern-day computational power to be applied to the problem of finding the critical solution from billions of possibilities.
- The **solution** is presented as an ‘adequacy factor’ (applied to one or more loads in the problem) and also displayed visually as a failure mechanism involving a number of solid elements which will rotate relative to one another. To facilitate rapid interpretation of the mode of response the failure mechanism can be animated.
- Many types of problems can be solved, including those involving walls, columns, holes and areas of differing thickness. The **problem geometry** can be specified using Wizards for common problems or alternatively by:
  - drawing the geometry on-screen using the mouse,
  - importing from a CAD (DXF) file.

  The geometry can subsequently be edited using the mouse or by editing coordinates.
- All **Materials** and reinforcement patterns are available by applying specified Mp values, (the user inputs pre-calculated moment capacity values for hogging and sagging in two directions). Orthotropic and skew reinforcement can be easily incorporated.
- LimitState:SLAB provides extensive support to users wishing to use **Partial Factors**:
  - user specified partial factor sets can be defined,
  - different partial factors can be defined for permanent, variable, accidental and favourable or unfavourable loads,
- LimitState:SLAB provides a comprehensive and easy to use GUI interface with fully selectable geometry objects, a Property Editor, Materials Explorer, Loads Explorer and drag and drop facilities. It also provides users with full Undo/Redo facilities and ability to recover lost work via an auto-saved recovery file.

- A comprehensive **Report** can be generated, with user control over what is included, and the unique ability to output free body diagrams for all solid elements which define the critical failure mechanism, with equilibrium equations to permit easy hand validation.
- Comprehensive guidance within the program in the form of messages, warnings and text descriptions. Where appropriate these are hyperlinked direct to relevant sections within the online help file.
- Choice of working in Metric or Imperial units.

1.4 LimitState:SLAB Terminology

LimitState:SLAB is designed to rapidly identify the critical failure mechanism in any concrete slab analysis problem. The following annotated image highlights the most important on-screen entities the user will encounter when using LimitState:SLAB:



```
PROBLEM SIZE (m):
x: 1.00000 y: 1.00000
CURSOR (m):
x: -0.44504 y: 0.28916
```

Property	Value
Nodal Density ⊟	Custom
Target Number	10
Scale Factor	0.693371
Project Name	New Project
Project Details ⊞	
pointer	0x0a6a1910
pointer1	0x00000000
pointer2 ⊞	
Shown	True

```
Load case  Partial factors  Iteration  Variables  Constraints  Solution  Violation%  Vars added  Cons added  Time(secs)
1          Unity            1          173        84           7.67      0           0           0           0.081

Adequacy factor on applied load(s) is 7.67
```

Figure 1.1: The main user interface objects in LimitState:SLAB

1.5 Using Help

Pressing F1 at any time gives users access to the online help facility, providing users with a convenient means of accessing material contained within the manual whilst using the software. The software also includes hyperlinks which link directly to relevant parts of the online help material (e.g. from within messages, dialogs and text descriptions), to provide users with rapid access to relevant explanatory material.

1.6 System Requirements

LimitState:SLAB runs on the Windows 7, 8.1 and 10 operating systems (support for Mac OSX and Linux operating systems is available on request, subject to demand). Recommended minimum system specifications are as follows:

- Intel or compatible processor (i3 or better recommended)
- 200 MB free hard disk space
- 4 GB RAM (8 GB recommended)

Note that the use of emulated platforms such as VMware is not supported.

1.7 Program Limits

The program uses a ‘Single Document Interface’ which means that one project file can be open in LimitState:SLAB at any given time. However, several instances of LimitState:SLAB can be opened simultaneously if required and each of these may contain a separate project file.

When using LimitState:SLAB with a ‘full’ license, problem size is limited only by available computer power.

1.8 Platform Limitations

1.8.1 Macintosh

The following are known limitations, or differences in behaviour, when being run on a Macintosh computer:

- Licenses tied to a USB dongle are not available (no supporting drivers).
- Animations cannot be exported to AVI.
- The colour palette does not contain a range of pre-defined colours.
- The layout of buttons is in Windows format (i.e. ‘OK - Cancel’ rather than ‘Cancel - OK’).
- Full screen mode is not supported.
- Hiding toolbars may cause white ‘shadows’ to be rendered at the top of the screen.

1.9 Contact Details

1.9.1 Sales

To request information on pricing, a formal quotation, or to purchase the software please contact LimitState Ltd, at **sales@limitstate.com**.

1.9.2 Software Support

Software support for LimitState:SLAB is available to all users with a valid support and maintenance contract. Additionally we are happy to help users with time-limited ‘trial’ or ‘evaluation’ licenses. All queries should be directed to **support@limitstate.com**.

1.9.3 Website

For the most up-to-date news about LimitState:SLAB, please visit the LimitState:SLAB website: limitstate.com/slab.

Chapter 2

Getting Started

2.1 Installation and Licensing

Details relating to the installation and licensing of LimitState software are provided in the separate ‘Installation and Licensing Guide’.

2.1.1 Thumbnails, Tags and File Search

For users running Windows 7 or above, the ability to include thumbnails and tags with the saved project is available[1]. Careful use of these features allows different LimitState:SLAB files to be categorized and later searched for on a computer, without the need to open and inspect each one individually. Additionally, other properties from the **Project details** dialog can be searched if the system properties are set appropriately.

2.1.1.1 Enabling Thumbnails

To allow a system to take advantage of the thumbnail feature it may be necessary to set it to display these instead of the program icon. To do this:

1. Open **Control Panel** on the PC.
2. Select **Folder Options**.
3. Select the **View** tab.
4. Ensure that **Always show icons, never thumbnails** is NOT selected.
5. Click OK.

For further information see Chapter 10. Note that uninstalling LimitState:SLAB may require a reboot to remove the thumbnails feature from Windows registry.

[1] For Windows Vista users, thumbnails may be available depending on the system configuration.

2.1.1.2 Enabling File Property Searching

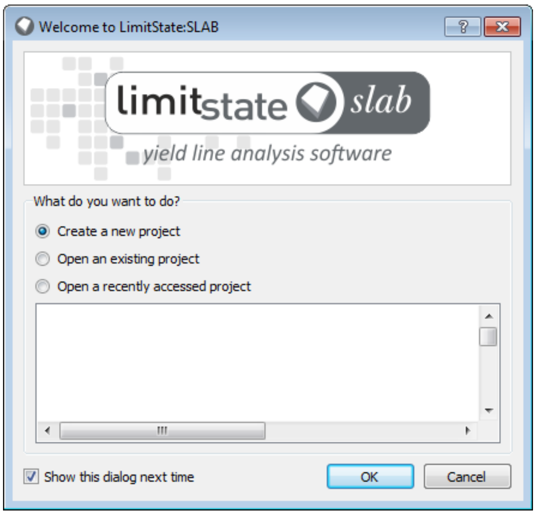
To allow a system to search within the **Project details** it may be necessary to change the default search settings. To do this:

1. Open **Control Panel** on the PC.
2. Select **Folder Options**.
3. Select the **Search** tab.
4. Ensure that **Always search file names and contents...** IS selected.
5. Click OK.

For further information see Chapter 10. Note that searching for file properties in a folder that is included in the Windows ”Index” may not work at first. This is because the system requires time to register the file properties in the index and, during this period, will not return matches. The expected behaviour will return once indexing has occurred.

2.2 Starting LimitState:SLAB

To start LimitState:SLAB, on the **Start** menu, point to **All Programs**, then click on LimitState:SLAB. On starting LimitState:SLAB the following welcome screen should appear (Figure 2.1).



What do you want to do?

● Create a new project
○ Open an existing project
○ Open a recently accessed project

☑ Show this dialog next time

Figure 2.1: LimitState:SLAB welcome screen

Users then have three options:

1. **Create a new project** - select this option and click **OK** to bring up the **New Project Dialog**. You may then select either an ‘Empty project’ (which provides you with full flexibility

to define the geometry of your problem), or one of the application-specific predefined projects, each of which will activate a wizard to guide you through the process of specifying your problem.

2. **Open an existing project** - select this option and click **OK** to display the open file dialog.

3. **Open a recently accessed project** - select this option, choose a file from the list and click **OK** to return to a recent project.

2.3 The Adequacy Factor

In order to drive a problem to failure, LimitState:SLAB must increase one or more loads to such a magnitude that the moment resistance provided by the slab is surpassed in enough locations to form a mechanism (i.e. a collapse state). The user determines which loads are increased in the analysis by setting the **Adequacy** property to *True*. Upon solve, the optimization process determines the lowest multiplier on these loads required to cause collapse. This multiplier is called the **Adequacy factor**.

The **Adequacy factor** can be interpreted in two different ways, depending upon the **Partial Factors** that have been set:

1. Unit Partial Factors

When all **Partial Factors** are set to 1.0 (Unity), the **Adequacy factor** reported is a basic multiplier on the applied loading.

For example, if a pressure load of 1kN/m^2 is applied and the **Adequacy factor** reported is 3.1, a total pressure load of 3.1kN/m^2 is required to cause collapse.

2. Non-Unit Partial Factors

When any **Partial Factors** are non-unit (i.e. not 1.0), the loads and / or material properties are factored in advance of the analysis. Therefore, the **Adequacy factor** reported must be greater than, or equal to, 1.0 in order for the system to be deemed ‘safe’.

More about the **Adequacy factor** is given in Section 6.2.

2.4 Guidance Available in this Manual

Guidance is available as follows:

1. For a Quick Start introduction to LimitState:SLAB refer to Chapter 3.

2. For a description of the theory underlying the solutions generated by LimitState:SLAB refer to the Theory chapters in Part II.

3. For guidance on using LimitState:SLAB to model a range of problem types refer to the Modelling chapters in Part III.

Chapter 3

Quick Start Tutorial

3.1 Introduction

This chapter is designed to provide users with an overview of the capabilities of LimitState:SLAB. It is recommended reading for new users and will prepare them to subsequently make use of some of the more sophisticated features of the program.

For the sake of brevity some topics are not discussed in depth in this chapter. For further information on all topics, the reader is referred to the Modelling Guide (Part III) and User Guide (Part IV).

3.2 Overview of the Modelling and Analysis Process

When starting to model a problem using LimitState:SLAB the option is either:

1. To use a built-in 'Wizard' to quickly define a basic problem, or
2. To build a model from scratch, using a geometry imported from a DXF file or drawn by hand.

The process involved in either case follows the outline below:

1. Define geometry.
2. Assign support conditions.
3. Assign material properties.
4. Define loading.
5. Set up load cases and partial factor sets.
6. Analyse.
7. Query post-solve information.

3.3 Getting Started

The following section describes how to set up and solve a problem in LimitState:SLAB. Users should follow instructions marked with a ▷ symbol. Note that the values assume that the user is working in metric units. Results may differ if using Imperial units.

It is assumed that the user is starting from the **Welcome to LimitState:SLAB** dialog.

Create a New Project:

▷ Select **Create a new project** and click **OK** to bring up the New Project dialog, (see Figure 3.1).

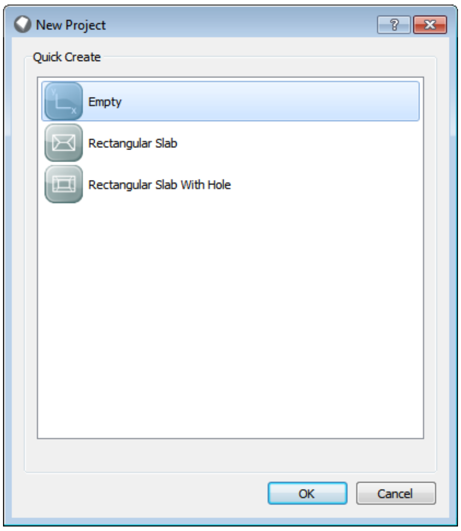


Figure 3.1: The LimitState:SLAB New Project dialog

If **Cancel** is selected, the user is free to define their own problem geometry. Alternatively, use of a wizard permits rapid definition of common problem geometries. The geometry can be easily amended subsequently.

3.3.1 Slab Geometry

▷ Select **Empty** and click **OK**.

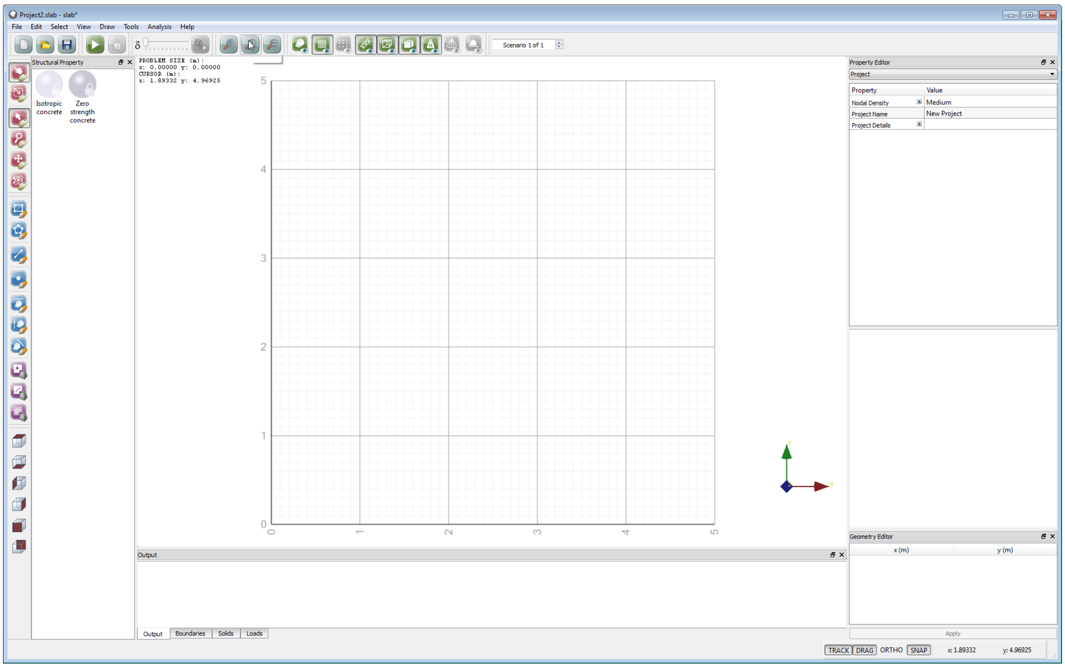
The **Empty Project Wizard** then appears. Project data is entered in two stages as follows (the icons in the navigation bar on the left hand side of the wizard will be highlighted during each stage of the problem definition):

Project Background details to the project may be entered here.

Draw Grid and object snap settings may be entered here.

▷ Click **Finish** to accept the default grid and snap settings.

A blank grid will be displayed in the main viewer (Figure 3.2):



```
PROBLEM SIZE (m):
x: 0.00000 y: 0.00000
CURSOR (m):
x: 1.89332 y: 4.96925
```

Property	Value
Nodal Density ⊞	Medium
Project Name	New Project
Project Details ⊞	

x: 1.89332 y: 4.96925

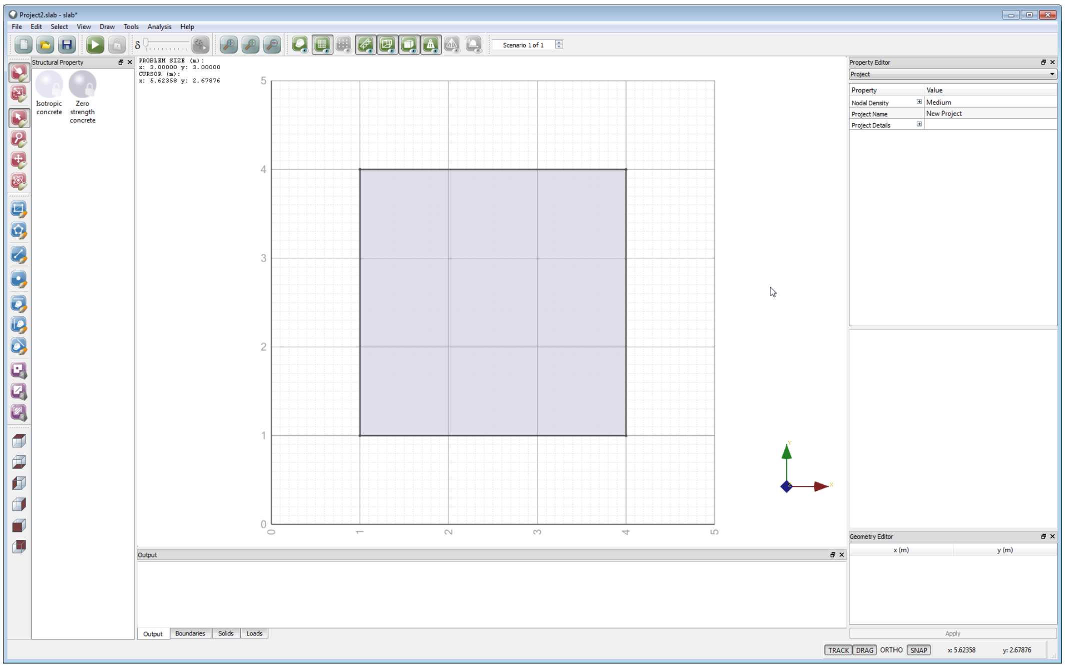
Figure 3.2: An empty project showing only a grid. Users can define their own slab geometry using the draw functionality.

Draw the Slab:

▷ Click on the **Draw Rectangle** icon .

▷ Click in the **Viewer Window** at location (1, 1). The first corner point of the slab should now be set.

▷ Move the mouse to position (4, 4). Click the mouse again to set the second corner of the slab (Figure 3.3).



```
PROBLEM SIZE (m):
x: 3.00000 y: 3.00000
CURSOR (m):
x: 5.62358 y: 2.67876
```

Property	Value
Nodal Density	Medium
Project Name	New Project
Project Details	

x: 5.62358 y: 2.67876

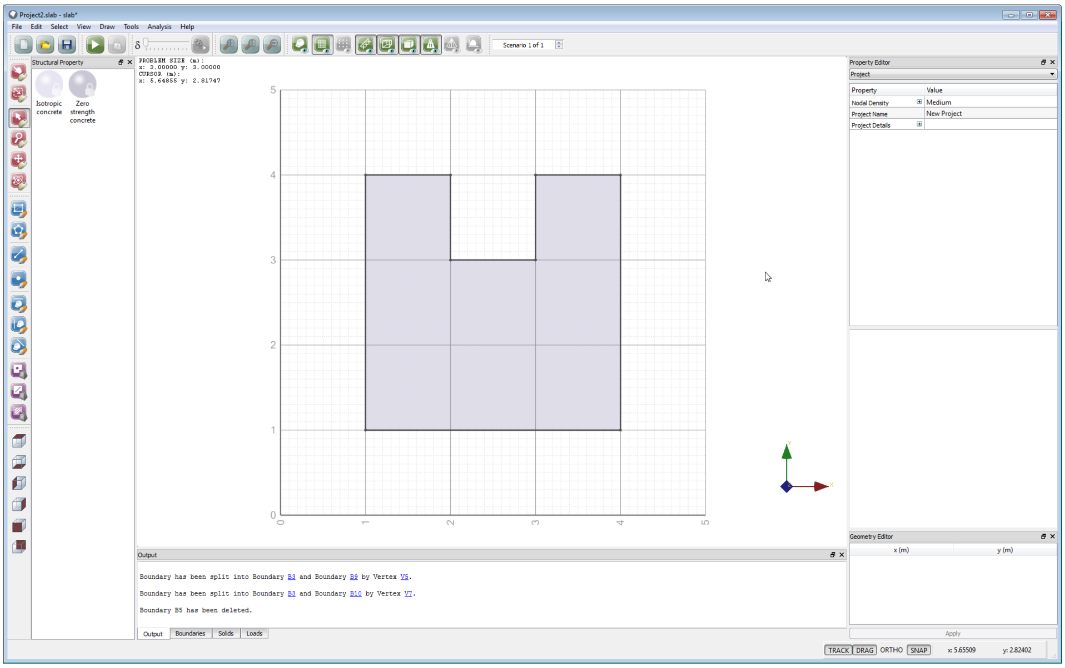
Figure 3.3: A square slab, specified using the ‘Draw Rectangle’ functionality.

Modify the Slab:

▷ Draw another rectangle, this time from (2, 3) to (3, 4).

▷ Click in the smaller square zone that is created (it will turn pink when selected).

▷ Press DELETE on the keyboard (alternatively, click the ☒ icon in the top toolbar). The small square will now be removed from the problem as shown in Figure 3.4.



```
PROBLEM SIZE (m):
x: 3.00000 y: 3.00000
CURSOR (m):
x: 5.64855 y: 2.81747
```

Property	Value
Nodal Density	Medium
Project Name	New Project
Project Details	

```
Boundary has been split into Boundary B3 and Boundary B9 by Vertex V5.

Boundary has been split into Boundary B3 and Boundary B10 by Vertex V7.

Boundary B5 has been deleted.
```

x: 5.65509 y: 2.82402

Figure 3.4: Remove a section of the slab, also using the ‘Draw Rectangle’ functionality.

3.3.2 Boundary Conditions

3.3.2.1 External Boundaries

External boundaries in LimitState:SLAB can take one of the following forms:

Free The boundary is free to displace and / or rotate in any direction.

Simple The boundary is fixed against displacements in all directions. Rotations of the slab around the axis of the boundary are permitted without yield-line formation.

Fixed The boundary is fixed against displacements in all directions. Rotations of the slab around the axis of the boundary are only permitted as a result of yield-line formation.

Partially Fixed The boundary is fixed against displacements in all directions. Rotations of the slab around the axis of the boundary are only permitted as a result of yield-line formation at a moment equal to the specified ratio multiplied by the strength of the adjacent slab.

Symmetry The boundary represents a line of symmetry in the model.

3.3.2.2 Internal Boundaries

Internal boundaries in LimitState:SLAB can take one of the following forms:

Free The boundary is free to displace and / or rotate in any direction.

Knife-edge The boundary is fixed against displacements in all directions. Rotations of the slab around the axis of the boundary are permitted without yield-line formation.

3.3.2.3 Lift-off

In certain circumstances it may be desirable to allow a slab to be supported from vertical downwards displacement, but for it to be able to move vertically upwards. By setting the ***Support lift-off*** field to *true*, LimitState:SLAB will permit this to occur.

Note that lift-off can only be specified for the following boundary types:

- **Simple** (external boundary)
- **Knife-edge** (internal boundary)

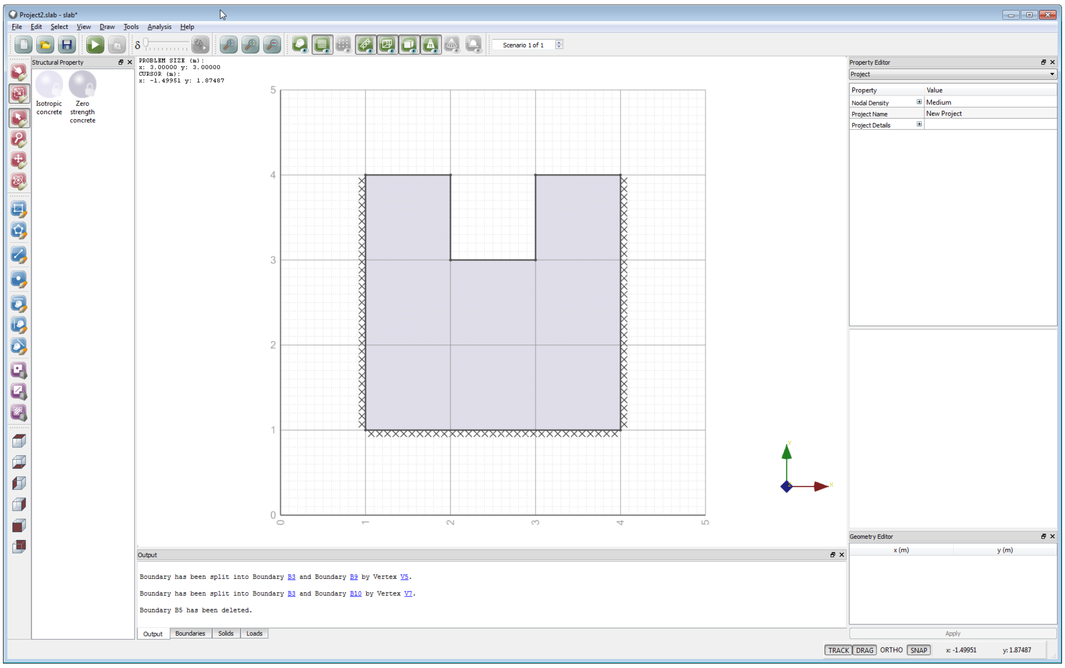
Set the Boundary Conditions:

▷ Ensure that **Click Select** is active (select the ↖ and ↘ icons).

▷ Hold down CTRL on the keyboard and click the left, bottom and right ***Boundaries*** (these will be highlighted pink once selected).

▷ In the **Property Editor** (at the right of the screen), the dropdown will read ‘External Boundaries (3)’. Double-click the ***Value*** field corresponding to the ***Support Type*** and select *Fixed* from the dropdown menu that appears.

▷ Click in the Viewer Window. The previously selected boundaries will now be fixed. This is denoted by cross-hatching (Figure 3.5).



```
PROBLEM SIZE (m):
x: 3.00000 y: 3.00000
CURSOR (m):
x: -1.49951 y: 1.87487
```

Property Editor: Project

Property	Value
Nodal Density ⊞	Medium
Project Name	New Project
Project Details ⊞	

```
Boundary has been split into Boundary B3 and Boundary B9 by Vertex V5.

Boundary has been split into Boundary B3 and Boundary B10 by Vertex V7.

Boundary B5 has been deleted.
```

Geometry Editor: x (m) y (m)

x: -1.49951 y: 1.87487

Figure 3.5: Cross-hatching along a boundary signifies a fixed boundary condition. Rotations along the axis of the boundary are only permitted as a result of yield-line formation.

3.3.3 Slab Definitions

Slab Definitions define the unit weight, thickness and moment resistance of a slab and can be assigned on a per-zone basis:

Name / **ID** A unique identifier / name

Color The color as displayed on screen

Unit Weight The unit weight of the slab in any area where this definition is applied

Thickness The thickness of the slab in any area where this definition is applied

Mp The plastic moment of resistance per unit length. To allow for the presence of skewed and orthotropic reinforcement, this is split into two directions named ***First*** and ***Second***. The following may then be defined for each:

- ***Mp***$^{+}$, The sagging plastic moment of resistance in the direction specified by the **Angle**.
- ***Mp***$^{-}$, The hogging plastic moment of resistance in the direction specified by the **Angle**.
- ***Angle (°)***, The angle (anticlockwise) described between the global x axis and the direction in which M$_p$ is acting. Note that this is NOT the angle of the reinforcing bars (α in Figure 3.6), rather it is the angle NORMAL to them (β in Figure 3.6).

By default, newly generated solid zones are not assigned any **Slab Definition**.

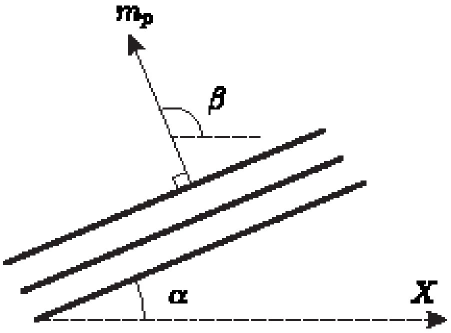


Figure 3.6: Direction of the moment capacity Mp

Built-in **Slab Definitions** are identified by the presence of a lock on their icon. The values of the attributes in a locked structural property cannot be changed. However, new slab definitions can be generated and assigned to zones in place of the default.

Add a New Slab Definition:

▷ Right-click in the **Slab Definitions Explorer** and select ***New slab definition*** from the context menu that is displayed.

▷ Ensure ***Flexural*** is selected in the *Type* dropdown.

▷ Name the slab definition ”Example Material” and provide a color

▷ Set the slab properties to be:

- Unit weight = 0.0 (i.e. assume it is weightless)
- Thickess = 1.0 (default value)
- First direction:
  - Mp^+ = 1.0
  - Mp^- = 0.5
  - Angle = 0 degrees
- Second direction:
  - Mp^+ = 2.0
  - Mp^- = 1.0
  - Angle = 90 degrees

▷ Click ***OK***.

Assign the New Slab Definition:

▷ In the **Slab Definition Explorer**, click and hold on the newly generated slab property.

▷ Drag the newly generated **Slab Definition** over to the slab in the **Viewer Window** and release the mouse button.

▷ The zone will now be assigned the new **Slab Definition** (the color will change).

Note that you can also change the **Slab Definition** assigned to a zone via the **Property Editor**.

3.3.4 Loading

Loading in LimitState:SLAB can take the form of:

Point Loads A single load applied at a specified location.

Line Loads A uniform load (i.e. load per unit length) applied between two specified locations.

Pressure Loads A uniform pressure load (i.e. load per unit area) applied to one or more specified solid zones within the problem.

Self-weight Loads Pressure loads resulting from the unit-weight and thickness of the slab. These can be applied on a per-zone basis.

3.3.4.1 Load Types

Loads (or actions) in LimitState:SLAB are assumed to take one of three **Types**, to which partial factors can be applied. These relate to the amount of time that the load is anticipated to be in contact with the structure and correspond to classifications common to many codes of practice, such as the Eurocodes:

Permanent A load or action that is expected to remain on the structure indefinitely (i.e. be persistent).

Variable A load that is expected to exist temporarily at the specified location on the structure.

Accidental A load that is expected to occur only in rare or exceptional circumstances.

3.3.4.2 Adding a Load

Adding loads to a problem requires two things:

1. Loads must be defined (in terms of magnitude and type) and added to the **Loads Database**.

2. **Load Cases** must be defined. This is done by selecting predefined loads from the **Loads Database** and applying them at specified locations in the model along with specified partial factors and other case-specific options.

LimitState:SLAB allows the user to define and copy loads across load cases using the **Load Case Manager**. Alternatively, a quicker option (for instances where the loading is relatively simple) is to use one of the loading icons in the user interface:

Point Load Add a point load at a specified location.

Line Load Add a line load between two specified points.

Pressure Load Add a pressure load to one or more zones.

Using this method, a load can be defined and added to both the **Loads Database** and the current **Load Case** in a single action.

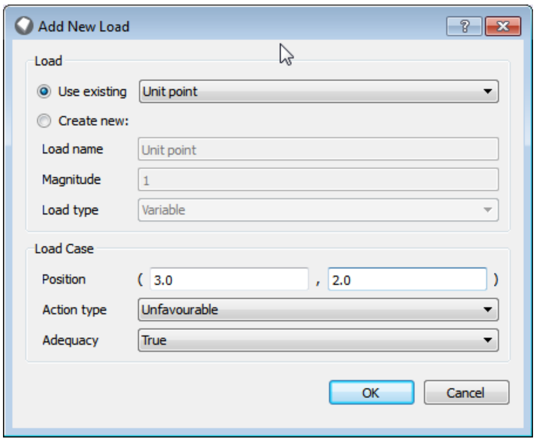
Add a Point Load:

▷ Click the **Point Load** icon, .

▷ Hover the pointer over the slab at position (3, 2) and click. This will bring up the ***Add New Load*** dialog (Figure 3.7).

▷ Choose *Use existing* Unit point (load) and confirm that the load position is correct. Leave the ***Action Type*** and ***Adequacy*** as their default values.

▷ Click ***OK***. A point load will now be created and displayed at location (3,2) (Figure 3.8). Note that, by default, all partial factors on load and material strengths are set to unity. To change this, open the **Load Case Manager** (via the menu item **Loads**). Here, existing or new partial factor sets can be assigned as necessary. For the purposes of this example the default settings will be used.


Add New Load

Load

● Use existing: Unit point

○ Create new:

Load name: Unit point

Magnitude: 1

Load type: Variable

Load Case

Position (3.0 , 2.0)

Action type: Unfavourable

Adequacy: True

Figure 3.7: Adding a new (unit) point load to the model.

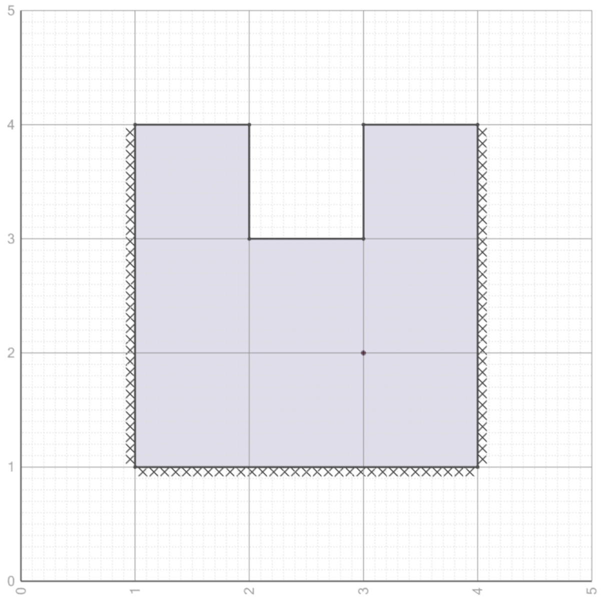


Figure 3.8: A point load displayed on the model at location (3,2).

3.3.5 Solving the Problem

The problem is now ready to be solved.

In order to analyse the ultimate limit state, at least one load in the problem must be increased until the collapse state is reached. In order to indicate to LimitState:SLAB which load this is to be, the **Adequacy** property must be set for at least one load. In this case the wizard has automatically set the **Adequacy** property for the point load applied to the slab. The returned Adequacy Factor is the factor by which that load must be increased in order to cause collapse. For further information on the Adequacy factor and its usage, see Section 6.2.

When the load was added (Section 3.3.4.2), the ***Adequacy*** variable was set to *True*. This means that the point load is subject to factoring during the analysis. (Note that any other loading with ***Adequacy***=*True* would also be factored during solve).

There are three methods by which the analysis can be triggered:

1. Go to the **Analysis** menu and select ***Solve***.
2. Press F5.
3. Click the ▶ icon.

Solve:

▷ Using one of the methods described, solve the problem.

The program will first display a series of nodes, superimposed on the geometry objects in the problem, and will then rapidly try out all possible combinations of yield-lines interconnecting the nodes to find the optimum solution. The program will gradually refine the failure mechanism until an optimal yield-line mechanism is found (Figure 3.9), together with an associated **Adequacy factor** (margin of safety) on the specified load.

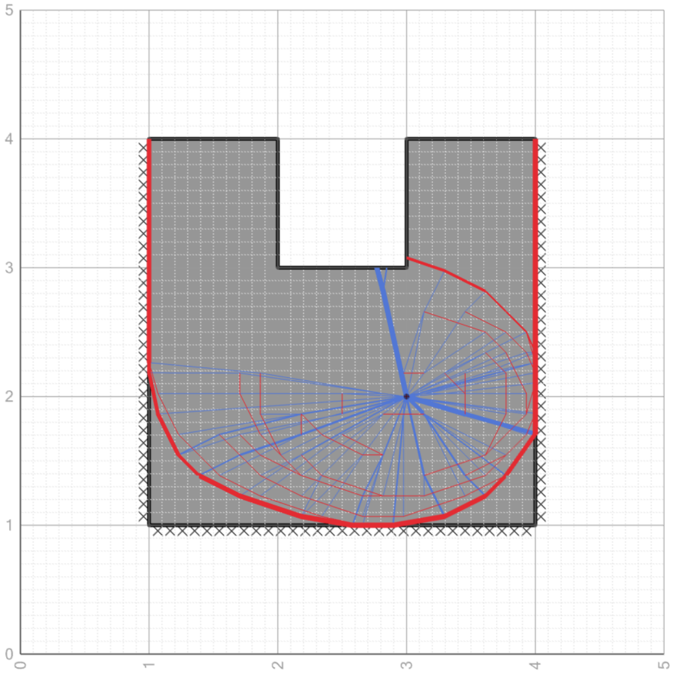


Figure 3.9: ‘Slab’ problem displayed in the main viewer (after analysis and before animation).

In the solution, red yield-lines denote failure by hogging and blue yield-lines represent failure in sagging. The thickness of the lines indicates the magnitude of the rotation, allowing the dominant failure mechanism to be clearly identified.

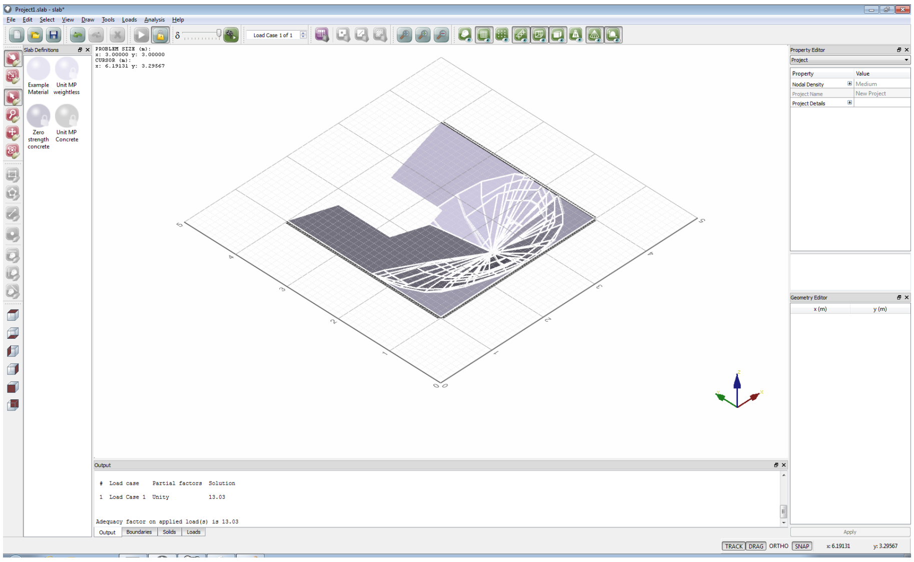
With the specified parameters, an **Adequacy factor** of 13.03 should be obtained (displayed in the **Output** window at the bottom of the screen). This means that the slab is safe against collapse until the point load has increased by a factor of approximately 13.03. As the problem involves unit partial factors, the **Adequacy factor** is a direct multiplier on the applied load.

In general, when non-unit partial safety factors are applied in the problem:

- Adequacy factor $>$ 1.0, the problem is safe against collapse
- Adequacy factor $<$ 1.0, the problem is unsafe against collapse.

3.4 Viewing Mechanism Deformation

By default the software will automatically animate the solution after solve (Figure 3.10), by magnifying the instantaneous displacements at failure. Note that although the solution is strictly only valid for infinitesimal displacements, large displacements are displayed to assist visualization of the collapse mode. For direct control over magnification of the mechanism displacements, the slider bar can also be used. The **Play Animation** button can be clicked to replay the animation.



```
PROBLEM SIZE (m):
x: 3.00000 y: 3.00000
CURSOR (m):
x: 6.19131 y: 3.29567
```

```
#  Load case    Partial factors  Solution

1  Load Case 1  Unity            13.03


Adequacy factor on applied load(s) is 13.03
```

Figure 3.10: 3D Deformation of the ‘Quick Start Slab’ problem

.

3.5 Viewing Post-Solve Information

Following analysis, a number of post-solve information becomes available to the user:

3.5.1 Yield-Lines

By clicking on an individual yield-line, the following information is shown in the **Property Editor**:

ID The name of the yield-line.

Start node Coordinates of the start of the yield-line.

End node Coordinates of the end of the yield-line.

Length The length of the yield-line.

Moment The moment experienced at the yield-line.

Rotation The instantaneous relative rotation along the yield-line.

▷ Click on any yield-line in the solved problem - inspect the available data in the **Property Editor**.

3.5.2 Bending Moments

After the software has solved a problem, the user is able to select any of the solids defining the failure mechanism (by clicking with the mouse). This will display a diagram of the bending moments acting around the edges of the selected object. Hovering over each part of the diagram will display the magnitude of the moment next to the mouse cursor.

3.6 Zooming In and Out

To zoom in and out, use the magnifying glass toolbar buttons (Zoom In , Zoom Out , Zoom All), or, if a scroll wheel mouse is being used, use the wheel to zoom in and out. Note that with the mouse, zooming takes place centred on the current position of the mouse pointer (the Select button must be on for this feature to work). Zoom All resizes the image to display optimally in the viewer. This is useful if the image has become too large or small.

3.7 Pan, Rotate and 3D Views

To pan, select the cross arrows toolbar button () and hold the left mouse button while dragging inside the **Viewer Pane**. Alternatively, if a scroll wheel / 3 button mouse is being used, click and hold the central button. The arrow keys on the keyboard will also change the view. Note that panning takes place centred on the current position of the mouse pointer.

To rotate the view in 3D, select the rotate toolbar button () and hold the left mouse button whilst moving the cursor in the **Viewer Pane**. To return the view back to the default, right-click in the **Viewer Pane** to bring up the context menu. From here, select ***View*** >***Front*** to return the display to the default viewing angle. Using the context menu, or the **View 3D** toolbar (Appendix B.3.2), it is also possible to snap the viewer to a number of pre-defined 3D viewing angles. These can be particularly effective when examining the solved problem.

3.8 Trying Different Problems and Parameter Sets

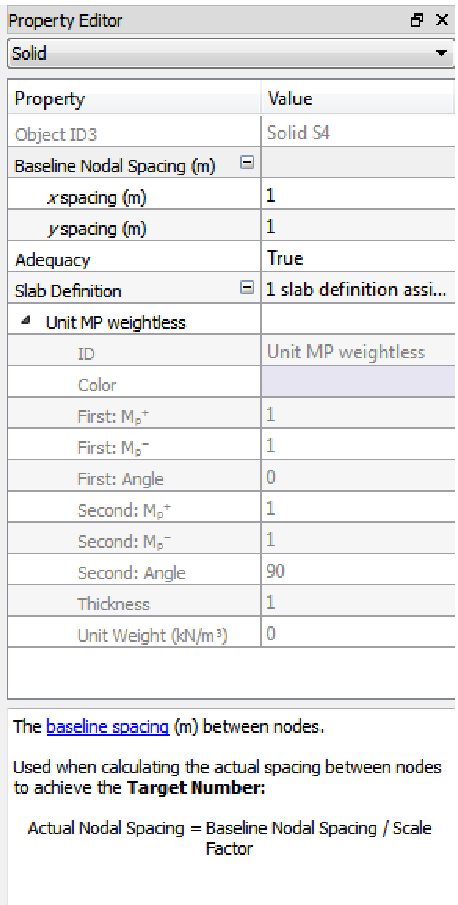
Modifications can be made to an existing project via the **Property Editor** and the solution can then be recalculated to reflect the changes.

Note that if there is a previously solved problem, the Unlock icon must be clicked to allow modification of any of the parameters; this is to prevent inadvertent alterations being made once a solution has been obtained.

To generate a new problem, click File>New or and select a wizard or Empty project.

3.9 The Property Editor

The **Property Editor** (**PE**), displayed on the right hand side of the display, allows the user to quickly read and / or modify the attributes of one or more objects within the current project. Figure 3.11 shows the typical parameters displayed in the Property Editor when a **Solid Object** is selected.



Property Editor

Solid

Property	Value
Object ID3	Solid S4
Baseline Nodal Spacing (m) ⊟	
x spacing (m)	1
y spacing (m)	1
Adequacy	True
Slab Definition ⊟	1 slab definition assi...
◢ Unit MP weightless	
ID	Unit MP weightless
Color	
First: M_p^+	1
First: M_p^-	1
First: Angle	0
Second: M_p^+	1
Second: M_p^-	1
Second: Angle	90
Thickness	1
Unit Weight (kN/m³)	0

The baseline spacing (m) between nodes.

Used when calculating the actual spacing between nodes to achieve the **Target Number:**

Actual Nodal Spacing = Baseline Nodal Spacing / Scale Factor

Figure 3.11: Parameters displayed in the LimitState:SLAB Property Editor when a **Solid Object** is selected.

Some of the functions in LimitState:SLAB are only accessible via the **Property Editor**. These are described in more detail in this section. Other functions and attributes can be accessed and modified elsewhere, but are shown for convenience in the **PE**.

Generally, when an object is selected, it will be highlighted and its properties will be displayed in the **PE**. Single clicking on any item in the 'Property' column gives an expanded explanation of the parameter in the window at the base of the **PE**. A ⊞ sign next to an item indicates that there are additional sub-parameters relating to that item that may be viewed. Click on the ⊞ sign to access these. Clicking on a value in the **PE** allows it to be modified by typing or selecting the required choice, unless it is a read only value or the project is **Locked**.

3.9.1 Changing Slab Definitions

By default the **Slab Definition Explorer** is located on the left hand side of the screen. This contains a list of available slab definitions.

Note that any system defined slab definitions (indicated by a padlock symbol:) are read only and may not be changed. User-editable copies may however be made or new definitions created as follows:

▷ Right-click on the ”Unit MP Weightless” icon and select *Duplicate slab definition*. Click the newly created definition (named ”Copy of Unit MP Weightless”) to view the properties in the **Property Editor**.

▷ Change the name of the definition and the color of the material.

▷ Change the values of one or more moment capacities. To do this, click on the field containing the value, enter a new value then press Enter or click elsewhere in the **Property Editor** to accept the value).

3.9.2 Changing the Slab Definition(s) Used in a Solid Object

▷ Unlock the problem and click anywhere in the slab solid in the viewer (to use single selection, ensure that toolbar buttons and are set to *On*).

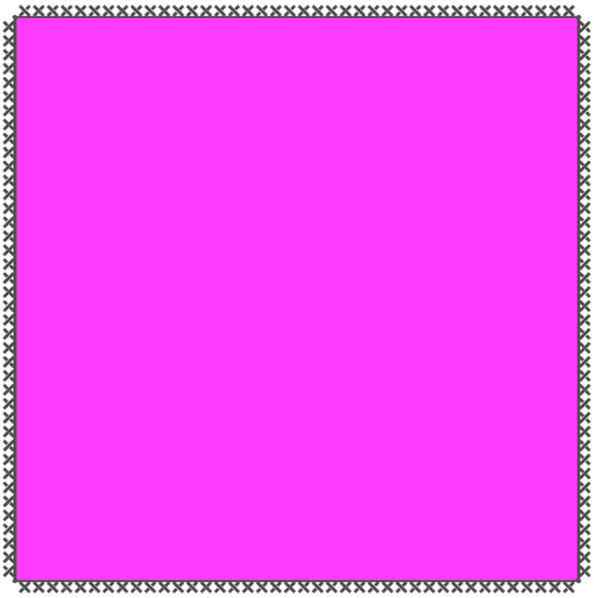


Figure 3.12: Problem geometry with slab solid highlighted following selection.

Once selected, the **Solid Object** representing the slab will be highlighted in pink (as shown in Figure 3.12), and its properties displayed in the **Property Editor**. To change the allocated slab definition, three options are available:

1. If a ***Slab Definition*** defined by the user (manually or in a wizard) has been selected, its properties may be freely edited directly in the **PE** in the same way as described in Section 3.9.1. (It is necessary to click the ⊞ sign next to the ***Slab Definition*** caption in the Property column of the **PE** to access the properties.)

2. If it is necessary to allocate an existing ***Slab Definition*** to the **Solid Object** representing the slab, 'drag and drop' may be used. Using the mouse, drag a structural object from the **Slab Definition Explorer** onto the **Solid Object** representing the slab. A dialog box will be displayed and the user asked whether the ***Slab Definition*** is to be replaced. Click **Replace** and the new structural object will be used in place of the previous one. The colour of the solid object should change to reflect the change in structural object (this will not be seen while the slab is still selected).

   ▷ Replace the default slab definition with **the new slab definition made previously**. After solving, the computed Adequacy Factor should have changed.

3. The third option, which is an alternative to drag and drop, is to click on the ***Value*** cell in the ***Slab Definition*** row in the **PE** (this should say '1 slab definition assigned...'). A **Change** button will appear. Click this and the **Edit Slab Definitions(s)** dialog will allow the selection of a slab definition (or set of slab definitions) that can be used in the slab solid.

3.9.3 Resizing a Solid

Changing the geometry of a problem is straightforward. Simply click on a **Vertex** of the slab and, with the left hand mouse button held down, drag this **Vertex** to a new location.

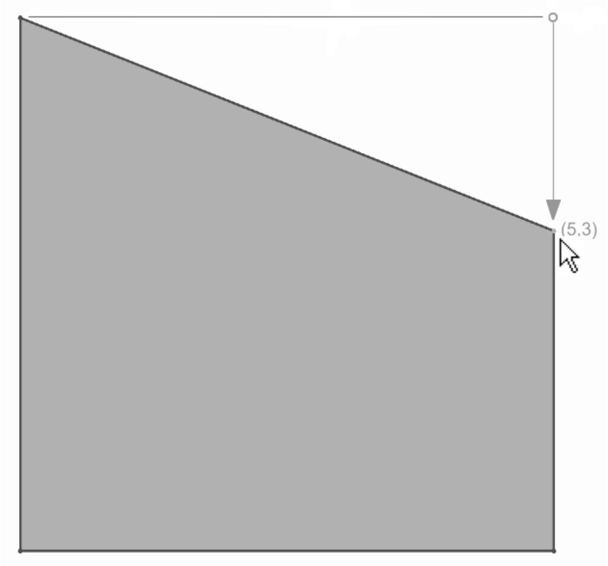
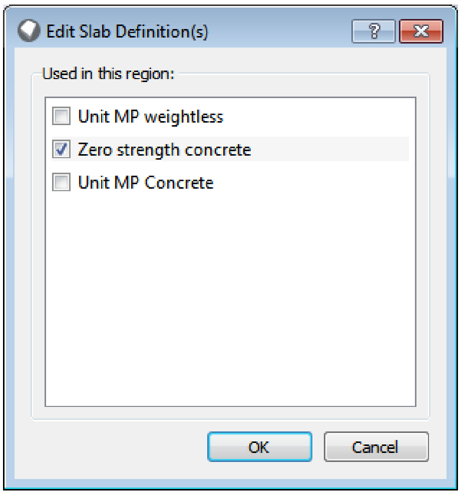


Figure 3.13: Moving a vertex by clicking and dragging in the viewer

3.9.4 Changing the Slab Definition Used on a Boundary

The **Slab definition** used on a boundary can be changed in one of two ways:

1. Click on a **Slab definition** from the **Slab Definitions Explorer**. With the left mouse button held down, drag the chosen definition over the boundary that you wish to modify. The boundary will turn pink. At this point, release the mouse button. The definition will be applied or, if a definition is already present on the boundary, a prompt will be displayed, asking if you wish to replace the existing definition.
2. Select one or more boundaries using the mouse (hold CTRL or use the ***Rectangle select*** for multi-selection). In the **Property Editor**, click the right-hand field next to the **Slab Definition** and select the **Change...** button that appears. A dialog will be shown (as depicted in Figure 3.14) which allows you to change the definition.



□ Unit MP weightless
☑ Zero strength concrete
□ Unit MP Concrete

Figure 3.14: Changing the Slab Definition used on a Boundary

3.9.5 Modifying Loads

Loads in LimitState:SLAB are defined via the **Loads Database** and the **Load Case Manager**. Refer to Chapter 17 for more information on how to work with loads.

3.10 Solution Accuracy

As with most numerical methods, solution accuracy is governed by the numerical discretization used in the underlying model.

With DLO the numerical discretization is controlled by the distribution of nodes within **Solid** and **Boundary** objects. Using the DLO procedure, the most critical mechanism that can be identified from the set of all potential yield-lines which interconnect these nodes is identified. In many cases a sufficiently accurate solution will be generated when a relatively coarse distribution of nodes is employed.

The number of nodes to be used can be controlled via the **Nodal Density** setting, accessible via the **Property Editor** under 'Project'. The basic settings are **Coarse**, **Medium**, **Fine** and **Very Fine**. To investigate the effect of nodal distribution on the problem in Section 3.3.5, set up a new problem. Solve and note the solution then click anywhere in an empty part of the **Viewer** pane (the part of the screen where the problem geometry is displayed). This will display the project level properties in the **Property Editor**. Change the value in the **Nodal Density** entry to **Fine**, and then solve the problem again. This time a similar but more detailed collapse mechanism is found and the associated adequacy factor is slightly lower.

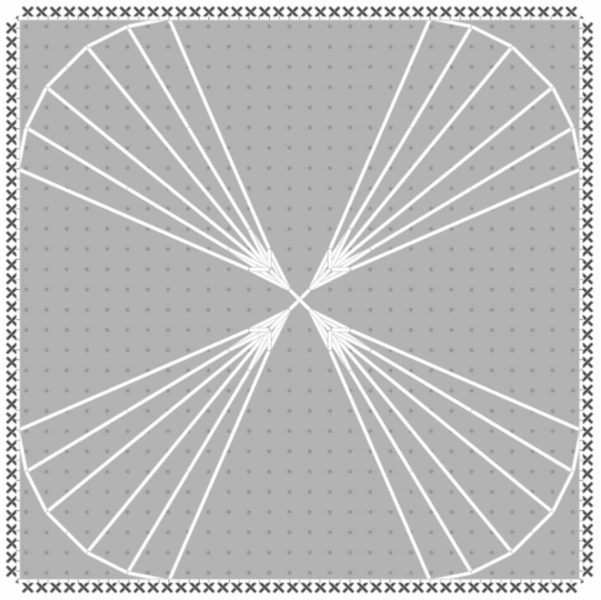


Figure 3.15: 'Simple Slab' critical yield-line pattern (after analysis with a *Fine* nodal resolution)

3.11 Conclusion

This brief quick start tutorial has been designed to familiarize users with the basic functionality of LimitState:SLAB. It is recommended that users experiment with the various wizards, and modify the parameters involved, before constructing problems from scratch.

Chapter 4

Wizards

4.1 Introduction

LimitState:SLAB provides a number of Wizards which allow the user to rapidly create models of commonly encountered problems. Variants on these geometries are easily generated by modifying the basic geometry created by the Wizard (see Section 14.6). To use a Wizard, select **Create a new project** in the **Welcome to LimitState:SLAB**dialog and click ***OK***, or, if the software is already running then click File>New or . The **New Project** dialog (Figure 4.1) will then start.

A number of different project types are available, all of which initiate a Wizard.

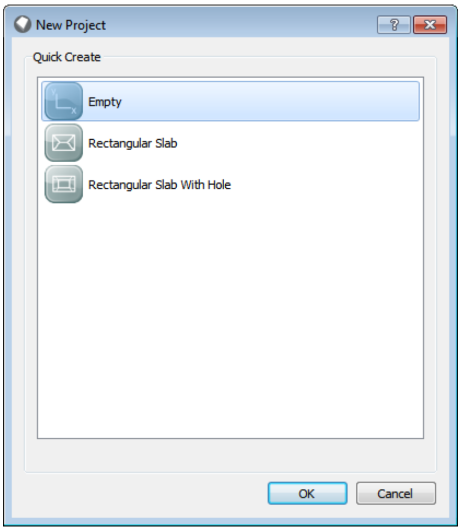


Figure 4.1: The **New Project** dialog

Empty Creates an empty project for the user to draw their own model. This includes options for specifying an underlying grid. It solves for the factor on applied loads.

Rectangular Slab Creates a model of a basic (skewed) rectangular slab. The default loading is set to vertical with a unit pressure.

Rectangular Slab With Hole Creates a model of a basic (skewed) rectangular slab with a hole. The default loading is set to vertical with a unit pressure.

Select the required Project Wizard and click ***OK***.

4.2 Using a New Project Wizard

4.2.1 Introduction

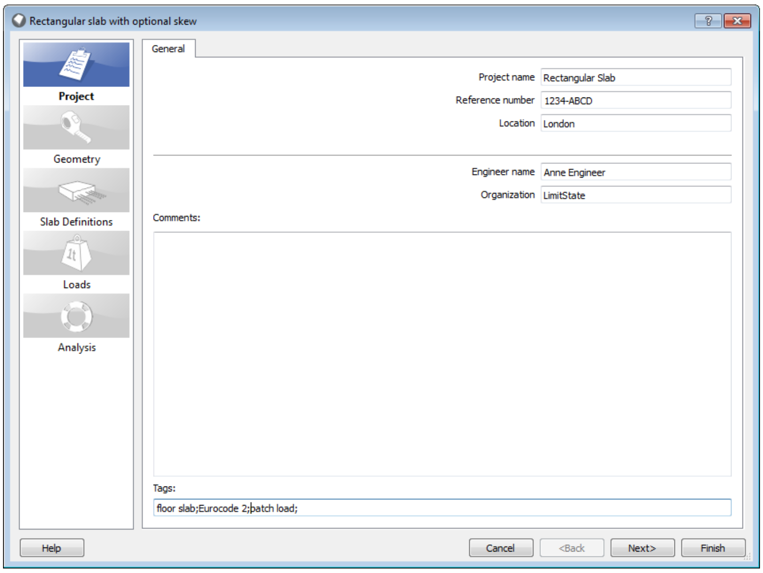
The Wizards in LimitState:SLAB are designed to help the user quickly generate a model of their problem.

Each Wizard guides the user through the process of defining the model:

- **Project** description (Section 4.2.2)
- **Geometry** (Section 4.2.3)
- **Slab Definitions** (Section 4.2.4),
- **Loads** (Section 4.2.5)
- **Analysis** (Section 4.2.6)

It should be noted that, at any point whilst running a Wizard, it is possible to click ***Finish***. LimitState:SLAB will automatically fill in any information that has not been explicitly supplied (by using default values together with information already provided by the user up until that point).

In most cases, information is entered in a sequential manner, the user clicking ***Next*** after each step. However, it is possible to move backwards through the various steps by using the ***Back*** button. The left-hand pane of the Wizard dialog serves as a reference point, with the current section being highlighted in blue as shown for the Project description stage in Figure 4.2.



Project name Rectangular Slab

Reference number 1234-ABCD

Location London

Engineer name Anne Engineer

Organization LimitState

Comments:

Tags:

floor slab;Eurocode 2;patch load;

Figure 4.2: Wizard dialog (Project tab)

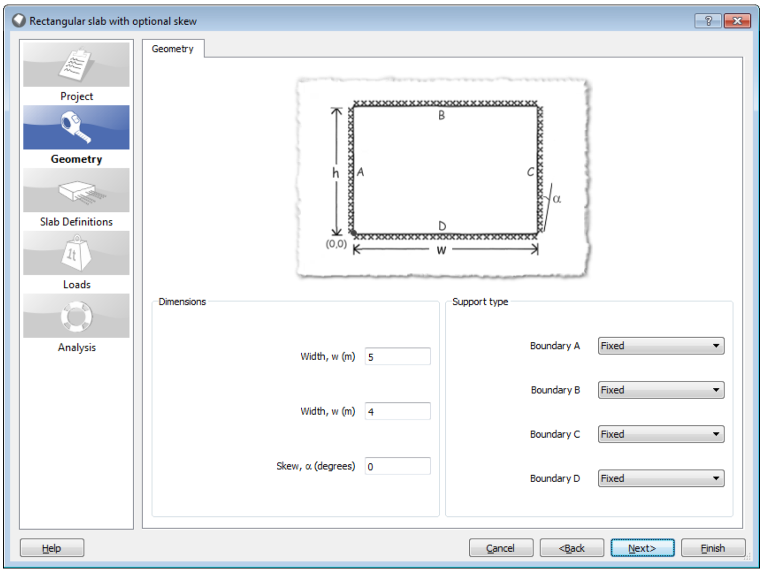
All parameters with dimensions should be entered in either Metric or Imperial units depending on the program preferences set by the user (see Section 13.1). When a data entry box is selected, data entry via a calculator is also available by clicking on the calculator button 🖩. The Calculator (see Section 8.10) also incorporates a unit converter for many commonly used units, including Metric and Imperial units.

4.2.2 General Project Settings

This dialog allows entry of the ***Project name***, ***Reference number***, ***Location***, ***Engineer name***, ***Organization***, general ***Comments*** and ***Tags***. This information may be included in the **Report** output (Section 20). For further details on the ***Tags*** functionality, see Chapter 10.

4.2.3 Geometry

The next stage is to describe the geometry of the problem. Figures in the dialog clearly indicate the meaning of the parameters to be entered, e.g. as shown in Figure 4.3.



Dimensions

Width, w (m) 5

Width, w (m) 4

Skew, α (degrees) 0

Support type

Boundary A Fixed

Boundary B Fixed

Boundary C Fixed

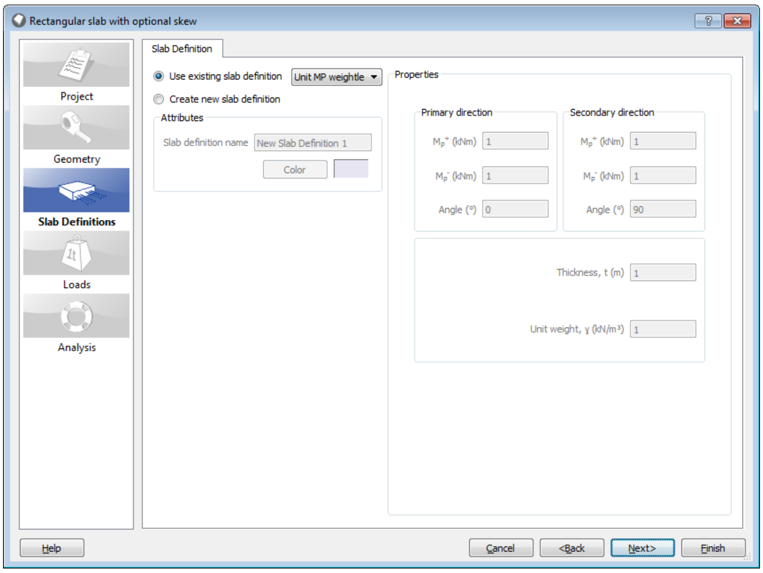
Boundary D Fixed

Figure 4.3: A typical wizard geometry dialog

The geometry data entry is normally designed to prevent unrealistic/impossible geometries being entered. However this is not feasible in all cases. If a combination of parameters is entered that would result in an unrealistic geometry being generated, a warning message will be displayed on pressing ***Finish*** and the software will adjust the geometry to produce a feasible result. The user may then either edit the final geometry directly (see Section 14.6), or, alternatively re-run the wizard.

4.2.4 Slab Definitions

Each tab in this dialog allows the user to specify the basic properties of the materials used in the problem or to select a material from a predefined list as shown in Figure 4.4.



● Use existing slab definition: Unit MP weightle

○ Create new slab definition

Attributes

Slab definition name: New Slab Definition 1

Properties

	Primary direction	Secondary direction
M_p^+ (kNm)	1	1
M_p^- (kNm)	1	1
Angle (°)	0	90

Thickness, t (m): 1

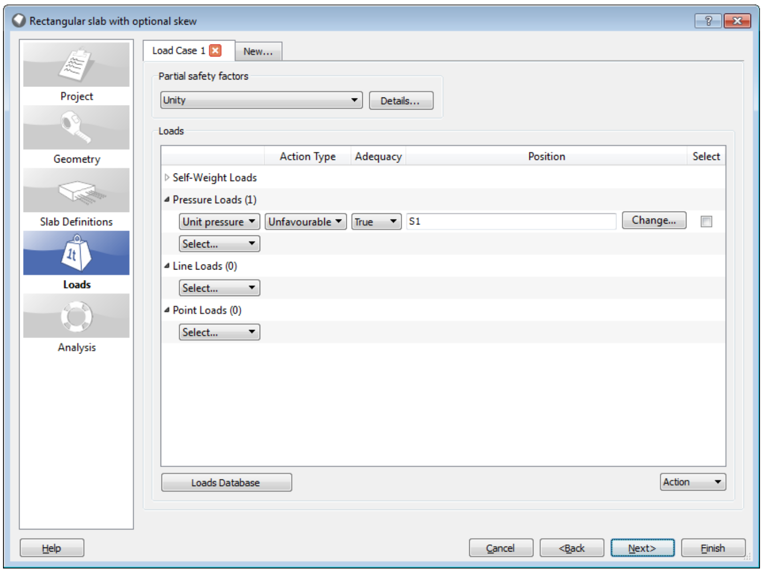
Unit weight, γ (kN/m³): 1

Figure 4.4: A typical Wizard materials dialog

In order to keep the Wizards straightforward to use, only basic material properties are entered, and default values are used for the other properties. To edit other available properties it is necessary to use the Property Editor once the Wizard has been exited.

4.2.5 Loads

Specify the required loads here as shown in Figure 4.5. Loads will generally by default have a margin of safety or **Adequacy factor** computed for them. For such loads, you may either enter the actual applied load and a margin of safety will be computed. Alternatively a value of 1.0 may be entered and the **Adequacy factor** will equal the collapse load. For further discussion of the **Adequacy factor** see Chapter 17.



Partial safety factors: Unity

Loads:

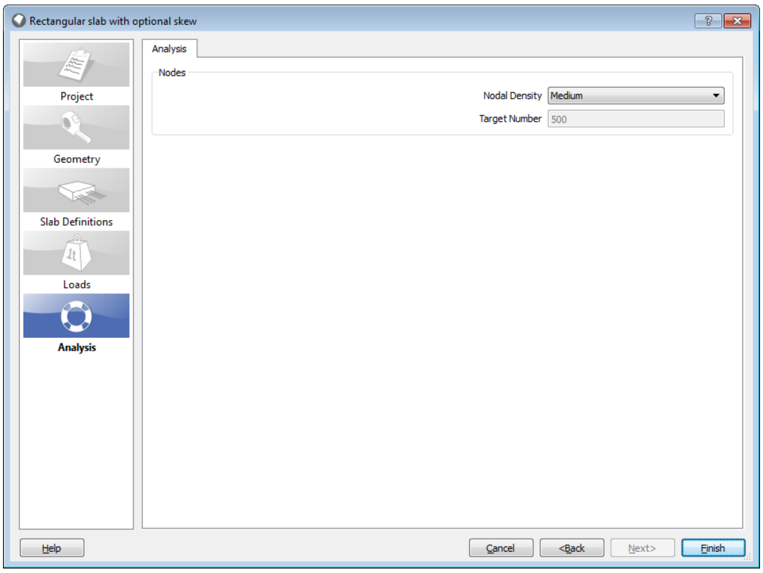
Action Type	Adequacy	Position	Select
Unit pressure	Unfavourable	True	S1

Figure 4.5: A typical Wizard loads dialog

4.2.6 Analysis

This stage displays the **Analysis** tab, as shown in Figure 4.6. Here the user can alter the nodal density of the problem.

By default the ***Nodal Density*** is set to *Medium* (500 nodes). The ***Target Number*** field will display the number of nodes associated with the selected density and, when a *custom* density is specified, the value can be set manually.



Nodal Density: Medium
Target Number: 500

Figure 4.6: A typical Wizard analysis options dialog

Part II

Theory

Chapter 5

Computational Yield-line Analysis

5.1 Introduction

The yield-line method is a long established, highly effective and widely used means of estimating the ultimate load carrying capacity of concrete slabs. The method was originally developed by Ingerslev (1923) and subsequently significantly enhanced by Johansen (1962). The upper bound status of the method within the context of the then emerging plastic theories of structural analysis was later confirmed by others (e.g. see Save et al. 1997). The method traditionally involves postulating a collapse mechanism which is compatible with the boundary conditions and then using equilibrium or the principle of virtual work to compute the ultimate load, or 'load factor'.

For certain special cases it has been possible to calculate provably exact failure load factors (e.g. by Fox 1974 for a uniformly loaded fixed square slab). However, in the case of most real-world geometrical configurations (for example slabs containing columns, holes etc), exact load factors are not available. In such cases unless the critical yield-line pattern is found, the computed load factor will over-estimate the true load factor. Whilst lower-bound methods can be used to bound the load factor from below, the gap between a yield-line solution and a solution obtained using common lower bound analysis methods (e.g. the strip method proposed by Hillerborg (1975), which simplifies the problem by allowing analyst/designer to select load paths whilst ignoring twisting moments) will typically be found to be quite wide. This situation is clearly unsatisfactory and has undoubtedly limited the extent to which hand-based yield-line analysis has been used in practice.

Consequently various computational methods have been applied to the problem over the past few decades. For example, rigid-plastic finite-elements were investigated in the context of reinforced concrete (RC) slab analysis by Anderheggen & Knopfel (1972). Their lower-bound method involved linearizing the yield function. More recently Krabbenhoft & Damkilde (2003) demonstrated that by using appropriate element formulations, and harnessing modern computational resources, that good lower bound approximations could be obtained using rigid-plastic finite elements. However, such rigid-plastic methods have not found their way into routine engineering practice and engineers typically instead have to rely on potentially cumbersome iterative elasto-plastic analysis methods. Furthermore, since finite element analysis is concerned with treatment of an underlying continuum mechanics problem, such methods do not explicitly identify patterns of yield-lines (though in many cases these may subsequently be inferred from the output).

To address this, computational methods which explicitly identify yield-lines have also been developed in parallel. For example, Chan (1972), and later workers such as Munro & Da Fonseca (1978) and Balasubramanyam & Kalyanaraman (1988), proposed methods in which potential yield-lines were placed at the boundaries of rigid elements in a finite element mesh. This permits LP to then be used to identify the most critical arrangement of yield-lines. Whilst available computing resources of the time meant that only relatively coarse meshes could be treated, the more significant problem with such methods is sensitivity of the results to the chosen mesh layout, with the consequence that refining the mesh alone does not necessarily lead to closer estimates of the collapse load factor being obtained. Despite numerous attempts to overcome this fundamental problem, using geometry optimization and other techniques (e.g. Johnson 1995, Thavalingam et al. 1999, Jochen & Wagner 2008), and claims of partial success, the reality is that none was entirely satisfactory. For example, after many years work in the field Johnson (2007) recently asserted that the upper bound problem was essentially 'too difficult' to solve computationally.

With Discontinuity Layout Optimization, the method used by LimitState:SLAB (see Section 5.2), a 'discontinuous' rather than continuum analysis approach is adopted, on the surface similar to the methods proposed by Chan (1972), Munro & Da Fonseca (1978) and others. However, the significant difference here is that by formulating the problem in terms of *discontinuities* rather than *elements,* a very much wider range of failure modes can be identified, thereby overcoming the element mesh layout sensitivity problems previously encountered.

5.2 Discontinuity Layout Optimization

5.2.1 Introduction

At the heart of LimitState:SLAB is a solution engine which uses the Discontinuity Layout Optimization (DLO) numerical analysis procedure to find a solution. The procedure was developed at the University of Sheffield and was first described for plane plasticity problems in a paper published in the Proceedings of the Royal Society (Smith & Gilbert 2007). In essence DLO can be used to identify critical yield-line failure mechanisms, output in a form which will be familiar to most structural engineers. However while traditional methods (e.g. Munro & Da Fonseca (1978)) can typically only work with mechanisms involving simple layouts (or patterns) of yield-lines, DLO has no such limitations. It can identify the critical failure mechanism for any problem, to a user specified geometrical resolution.

Unlike the method of Munro and Da Fonseca, in the DLO procedure the problem is formulated in terms of potential discontinuities rather than in terms of 'elements'. The potential discontinuities are free to crossover one another, giving a far wider search space and allowing complex yield-line patterns (e.g. involving 'fan' mechanisms etc.) to be identified without difficulty, and without the need to use tailored meshes etc. Also, the problem posed can be solved using simple linear optimization techniques, ensuring that a globally optimal solution is obtainable. When the work method is used, the objective of the optimization is to minimize the internal energy dissipated along yield-lines, subject to nodal compatibility constraints.

5.2.2 How Does it Work?

Discontinuity Layout Optimization (DLO), as its name suggests, involves the use of rigorous mathematical **optimization** techniques to identify a critical **layout** of lines of **discontinuity** which form at failure. When the technique is applied to structural stability problems involving reinforced concrete slabs, these lines of discontinuity are 'yield-lines' and define the boundaries between the moving rigid solid elements which together define the mechanism of collapse. Associated with this mechanism is a collapse load factor, which will be an upper bound on the 'exact' load factor according to formal plasticity theory. Thus in essence the procedure replicates and automates the traditional 'upper bound' hand limit analysis procedure which has been used by structural engineers for many years.

In order to allow a wide range of different failure mechanisms to be identified, a large number of potential lines of discontinuity must be considered. In order to achieve this, closely spaced nodes are distributed across the problem domain and potential lines of discontinuity are created to connect each node to every other node, thereby providing a very large search space. In numerical terms, in a problem containing n nodes, there are approximately $n(n-1)/2$ possible yield-lines and approximately $2^{n(n-1)/2}$ possible yield-line mechanism topologies. Thus, for example, 500 nodes give rise to ≈125,000 possible yield-lines and of the order of 2^{125000} possible mechanism topologies (including mechanisms which are not kinematically admissible).

A simple example of the DLO procedure involving a simply supported rectangular slab is given in Figure 5.1. Various steps are involved: (a) the problem geometry and boundary conditions are prescribed; (b) the slab is then discretized using a set of nodes; (c) the nodes are then interconnected with potential discontinuities; (d) the critical subset of these is identified using optimization. Whilst there is no restriction on the form of nodal distribution utilized, uniform square grids are generally most convenient and hence are used in LimitState:SLAB, with nodes being aligned along lines parallel to the global x and y axes. Although the solution will be influenced somewhat by the starting positions of the nodes, when fine nodal refinement is used, the exact positions of individual nodes will have relatively little influence on the solution generated.

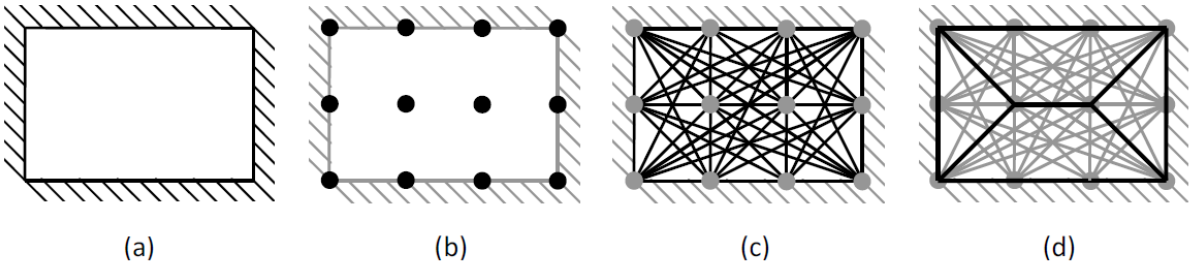


Figure 5.1: Stages in DLO procedure: (a) starting problem, e.g. here with simply supported edges; (b) discretization of slab using nodes; (c) interconnection of nodes with potential discontinuities; (d) identification of critical subset of potential discontinuities using optimization (giving the critical yield-line pattern)

In the DLO procedure the problem is formulated in entirely in terms of the relative displacements along discontinuities, e.g. each potential line of discontinuity can be assigned one or more variables that define the relative movement along that discontinuity. Compatibility can then be straightforwardly checked at each node by a simple linear equation involving these variables. Finally an objective function may be defined in terms of the total energy dissipated due to rotation along all discontinuities, a linear function of the displacement variables. A linear optimization problem is thus defined, the solution of which identifies the optimal subset of discontinuities that produce a compatible mechanism with the lowest energy dissipation (thick lines in Figure 5.1d). Details of the mathematical formulation are provided in Appendix C.

The accuracy of the solution obtained depends on the prescribed nodal spacing. A key benefit of the procedure, compared with comparable 'element based' procedures, is that singularities can be identified without difficulty (e.g. potential fan zones centred on a given node can be identified by linking multiple lines of discontinuity to that node). Finally, while the fact that discontinuities are clearly free to 'cross over' one another might appear problematic, it can be shown that compatibility is implicitly enforced at 'cross over' points, and their presence is very beneficial as the search space is dramatically increased. Further discussion of this issue and a detailed description of the DLO procedure is given in Smith & Gilbert (2007).

5.3 Limit Analysis: Advantages and Limitations

5.3.1 Introduction

The following subsections discuss some of the advantages and disadvantages of limit analysis. (Note that this is not intended to be an exhaustive discussion.)

5.3.2 Simplicity

Unlike elasto-plastic finite element analysis procedures, which typically require many iterations in order to arrive at a solution, numerical limit analysis identifies the solution directly by combining optimization techniques with rigorous plasticity theory. Limit analysis thus has the advantage that a solution can normally be determined rapidly and robustly, without suffering from numerical instability problems. Formulated as a linear programming problem, the procedure can also be guaranteed to find the global optimum solution, for a given nodal discretization.

Limit analysis also has the advantage that it typically only requires one strength parameter for any material modelled, e.g. the plastic moment of resistance (M_p). However more complex yield surfaces may alternatively be specified in principle.

5.3.3 Stress States in Yielding and Non-Yielding Zones

In the context of DLO the aim is to find a mechanism that results in collapse under the lowest load. The corollary of this is to find a network of discontinuities where the stress state is on the point of yielding. Solutions can thus be used to correctly represent moment distributions in yielding (failing areas). Outside these areas the solver needs only to find a set of moments that are in equilibrium and do not cause yield, no other conditions being stipulated. If stresses in these areas are examined, then erratic distributions may be observed. This is not an error, but an inherent result of the application of plasticity theory which is only concerned with the collapse state.

Thus LimitState:SLAB will generate suitable moment distributions that can be used to check the ultimate limit state in a structural element, but it should not be used (or expected) to generate force distributions for determining deflections in structural members that are not yielding or are adjacent to yielding areas.

Part III

Modelling

Chapter 6

General Principles

6.1 Model Definition and Solver

6.1.1 Model Definition

Problem geometries are built up using **Geometry objects**. The three key geometry objects relevant to model definition are:

Solid This is a 2D polygon defining an area of slab, column, drop panel etc. Its extent is defined by the surrounding **Boundary** objects.

Boundary This is a straight line that defines the edge or boundary of a **Solid**, or an interface between two **Solids.**

Vertex This is a 1D point that defines the end of a **boundary**.

Generally the problem will be defined in terms of **Solid** objects. **Boundary** objects are automatically generated around **Solid** objects. Single **Solid** objects should be used for bodies of one structural object type. A simply-supported slab problem may thus consist of one solid, while a problem involving a supporting column might consist of two or more solids, the slab, the column and potentially a drop panel.

Boundary objects can be used to define boundary conditions (e.g. simple support, fully fixed, symmetrical or free). They may also be used to define lines of support within the problem domain (i.e. between two **Solid** objects). All **Boundary** objects must exist as part of a **Solid.**

Vertex objects can only exist as part of a **Boundary** object.

6.1.2 Solver Specification

The specification of the LimitState:SLAB solver is as follows:

1. The software is designed to generate the optimal layout of yield-lines that make up the critical or failure mechanism for a specified problem.
2. The yield-lines are restricted to those that connect any two nodes within a pre-defined grid.
3. Yield-lines are restricted to those that connect nodes within a single **Solid** object, or between a node within a **Solid** object, and a node lying on an adjacent **Boundary** object.
4. The solution is given in the form of an **Adequacy** factor. This is the factor by which a specified load or material self weight (or combinations thereof) must be multiplied by to cause collapse.

Solutions are generated using the upper bound theory of plasticity. Plasticity theory is a common technique utilized in structural engineering. It is assumed that the user is fully familiar with the advantages and limitations of plasticity theory. Discussion of some of the advantages and limitations may be found in Section 5.3.

6.2 Adequacy Factor and Factors of Safety

6.2.1 Introduction

Various different definitions of factors of safety (FoS) are used in structural engineering; e.g. two alternatives are listed below:

1. Factor on load.
2. Factor on material strength.

The calculation process used to determine each of these factors for any given problem will in general result in a different failure mechanism, and a different numerical factor. Each FoS must therefore be interpreted according to its definition.

In general any given design is inherently stable and will be well away from its ultimate limit state. Therefore, in order to undertake a ULS analysis it is necessary to drive the system to collapse by some means. There are two general ways to drive a system to ULS corresponding to the two FoS definitions previously mentioned:

1. Increasing an existing load in the system
2. Reducing the material strengths

LimitState:SLAB solves problems using Method 1 by application of the **Adequacy factor** to designated loads. However it can be straightforwardly used to find the other type of Factor of Safety.

Note that partial factor based design codes such as Eurocode 1 do not explicitly compute a factor of safety, but pre-apply factors to problem parameters. Application of this approach in LimitState:SLAB is described in more detail in Section 6.3.

6.2.2 Method 1 - Factor on Load

The question that is posed by Method 1 is as follows:

How much bigger does a particular load (or set of loads) on the slab need to be to cause collapse, or, by what factor a does the load need to be increased to cause collapse?

The factor a is the same as the **Adequacy** factor as reported by LimitState:SLAB.

6.2.3 Method 2 - Factor on Strength

The question that is posed by Method 2 is as follows:

How much weaker does the slab need to be under the design load to cause collapse, or, by what factor F does the slab strength need need to be reduced to cause collapse?

The factor F is the factor of safety on strength.

If it is required to determine the Factor of Safety on the slab strength in LimitState:SLAB, then the recommended approach is to set up a series of Load Cases with partial factors on material properties across a suitable range according to problem type. The solution that produces an **Adequacy factor** of 1.0 is the Factor of Safety on slab strength. It may be necessary to interpolate results to determine the Factor of Safety.

6.2.4 Application of the Adequacy Factor

The **Adequacy** factor may be applied to one or more of the following parameters that result in a force within a problem:

1. an applied load (pressure, line or point),
2. a self weight.

In many problems, the **Adequacy** factor will be applied to a load. For problems where there is no externally applied load, then the **Adequacy** factor may be applied to a self weight.

Where the **Adequacy** factor is applied to more than one parameter, then it is applied equally to each.

6.2.5 Adequacy Factor Sensitivity

As has been previously mentioned, LimitState:SLAB provides solutions in terms of **Adequacy** Factor. An **Adequacy** Factor may be applied to any load or to the self weight of any body of material. The **Adequacy** Factor that is returned by LimitState:SLAB when it has completed solving is the factor by which all the specified loads/self weights must be multiplied to cause collapse. The **Adequacy** Factor is similar to a Factor of Safety on *load*.

It is important to note that if there are several actions driving collapse, but an **Adequacy** Factor is applied only to one of them, then the **Adequacy** Factor may seem to have a misleadingly high sensitivity to parameter changes.

6.2.6 Adequacy Factor Direction

Occasionally, LimitState:SLAB may generate a failure mechanism that is unexpected by the user. This can sometimes relate to how the **Adequacy** factor is used.

When an **Adequacy** factor is applied to a load or self weight, then associated with the factor is an Adequacy Direction (AD) . This direction is defined as follows:

Load The AD is in the direction of application of the load and relates to the area of application of the load only. Essentially this will be downwards (z direction) for positive loads and upwards for negative loads.

Material Self Weight The AD is directed vertically downwards (z direction) and relates to the entire zone or zones to which the **Adequacy** factor is applied.

The mathematical formulation of DLO utilised in LimitState:SLAB requires that the identified critical failure mechanism must result in net positive work being done by the parameter(s) to which the **Adequacy** factor is applied. In simple terms it means that the failure mechanism must result in collapse that involves net movement in the AD.

In slab problems this is almost always in a downward direction and the issue of AD is not important. However a challenge may arise for example if it is required to determine the magnitude of an upward supporting force that is required to prevent overall downward collapse. It is not possible to simply reverse the direction of the supporting force to which the **Adequacy** factor is applied. In this case LimitState:SLAB will return the **Adequacy** factor required to generate overall upwards collapse (since only positive values of **Adequacy** factor can be found).

A solution to this challenge is to duplicate the supporting force, set this to a large value and do not apply an **Adequacy factor** to this duplicate force. Then apply a unit (downward) value to the supporting force and apply the **Adequacy factor** to this quantity. This will ensure that the AD is downwards. The difference between the large, fixed value and the **Adequacy factor** obtained is then the solution sought. Note that 'Adequacy = true' should not be set for any other load in the model.

Finally it should be noted that where an **Adequacy** factor is applied to more than one parameter, then the identified collapse mechanism must involve movement in at least one of the specified **Adequacy** directions.

6.3 Use of Partial Factors

6.3.1 Introduction

LimitState:SLAB is designed to work closely with the Eurocode approach to Ultimate Limit State design. It has therefore adopted the Eurocode definitions of actions and partial factors, which may be used if required in any analysis. These are sufficiently broad based to cover the needs of most other design codes.

While definitions may be taken from the Eurocode, the use of partial factors is common among many major international codes, hence LimitState:SLAB can be used in compliance with almost any design codes, some of which are pre-set into the software for convenience.

In the Eurocodes, partial factors are pre-applied to loads and/or material properties prior to analysis. Assessment of safety is then undertaken by testing whether in the subsequent analysis, the available resistance to collapse exceeds the actions causing collapse. In LimitState:SLAB this is equivalent to checking whether the **Adequacy** Factor (applied to any unfavourable load or self weight), is greater than 1.0.

The setting of Partial Factor values is carried out using the **Load Case Manager** (this can be found under the **Loads** menu item).

The general principles implemented in LimitState:SLAB are described below. However with respect to Eurocode 2: Design of Concrete Structures (Standard 1991) the following is not to be taken as a definitive guide. The engineer is expected to apply their own understanding of the Eurocodes, especially with regard to some of the subtleties that can arise in certain situations. i.e. if there appear to be inconsistencies between what is described below and what is documented Eurocode 2, then the Eurocode should be followed.

6.3.2 Factoring of Actions (Loads)

Eurocode 2 specifies three different types of actions (load types). These are all available within LimitState:SLAB:

1. Permanent
2. Variable
3. Accidental

The relevance of each action is the nature of the partial factor to be applied to it, with the corresponding values taken from the **Load Case Manager**. A Variable action will typically have a higher partial factor applied to it in comparison to a Permanent action.

Actions may be point, line or pressure loads or may arise from the self weight of a block of material. Self weights are regarded as Permanent actions in LimitState:SLAB.

Eurocode 2 also requires that each action is assessed as to its effect on the overall stability calculation. If it contributes to stability then it is Favourable, if it contributes to collapse then it is Unfavourable. Its **Action Type** affects the value of partial factor to be applied to it. The following **Action Types** may be applied to any **Loads**:

Favourable: Apply the favourable partial factors to any loads or to the self weight of the materials within a solid.

Unfavourable: Apply the unfavourable partial factors to any loads or to the self weight of the materials within a solid.

Neutral: Do not apply any factors to the loads or to the self weight of the materials within a solid. (N.B. the type of action, permanent, variable or accidental has no relevance in this case.)

By default, loading on all **Loads** are set to **Neutral** when they are first created. It is up to the user to explicitly set them to **Favourable** or **Unfavourable** if required.

The purpose of the **Neutral** setting is to:

1. ensure that settings for any new problems that do not require analysis with partial factors, remain unambiguous and unaffected by partial factors.
2. ensure that for any problem that is to be analysed using partial factors (such as when using Eurocode), that the user must make explicit decisions about the nature of the actions i.e. change the setting to either **Favourable** or **Unfavourable**.

Automatic factoring of *source actions* only (rather than *action effects*) is implemented in LimitState:SLAB.

Note that in the Wizards, external and self weight loads are preset to be **Unfavourable**. However, for certain problems it can be unclear at the start whether a particular load or self weight is **Favourable** or **Unfavourable**. LimitState:SLAB provides additional assistance in these cases. Following determination of the collapse load, LimitState:SLAB performs a check on all external actions to determine whether they acted favourably or unfavourably. If these are inconsistent with the original specifications, then the user is alerted to this and may alter the specification and re-solve.

In a very small number of cases it is possible that the amended Favourable / Unfavourable settings may result in a different collapse mechanism and another set of inconsistent Favourable / Unfavourable settings. This is not a inherent problem with LimitState:SLAB but simply a consequence of the Partial factor values. As always in these cases it is up to the engineer to apply their own judgement consistent with the principles underpinning the design code.

6.3.3 Factoring of Material Properties

Partial factors may also be applied to material properties i.e. the plastic moment of resistance M_p.

6.4 Solution Accuracy

6.4.1 Introduction

This section discusses solution accuracy within the context of the DLO numerical method itself.

As with any numerical method, solution accuracy is dependent on the resolution of the underlying model. With DLO this relates to the distribution of nodes within **Solid** and **Boundary** objects. The method will provide the most critical failure mechanism that can be generated using yield-lines interconnecting pairs of nodes. In many cases a sufficiently accurate solution will be generated using a coarse distribution of nodes. To assess solution accuracy, it is recommended that the nodal resolution be progressively refined, thereby allowing an assessment of the convergence characteristics to be made (towards the 'exact' solution).

6.4.2 Benchmarking Results

LimitState:SLAB is benchmarked against a set of known limit analysis solutions from the literature. Reference to these results can provide useful guidance as to the expected accuracy of the software over a range of problem types. For more information see limitstate.com/slab/verification.

6.4.3 Interfaces

To maximize computational efficiency, the solver does not model yield-lines that cross the interface (**Boundary** object) between one solid and another. The smoothness of the solution in the vicinity of the boundary is thus dependent on the nodal density on that boundary. LimitState:SLAB automatically assigns a higher nodal density on boundaries and the net effect on the solution is usually very small. However for coarse nodal resolutions, the effect can be noticeable. Thus if a **Solid** object is split in half by a new **Boundary** object, then the value of the solution may increase slightly. The user may individually set the nodal density on boundaries.

6.4.4 Small Solid Areas

As with all numerical software, numerical tolerance issues can cause the generation of unexpected results. This can occur when the software attempts to compute solutions based on numerically very small problem sizes. LimitState:SLAB has been designed to calculate failures for typical slab and, to assist users, LimitState:SLAB undertakes a pre-solve check and issues a warning when the total area of the problem is less than 0.25 m^2. If the total area is less than 0.00025 m^2, then a warning is issued.

6.4.5 Singularities

The DLO procedure is particularly suited to identifying solutions containing singularities, e.g. fan zones. However it must be noted that stress levels can increase greatly around the fan. This means that solutions with singularities may be particularly sensitive to the number of yield-lines and thus nodal resolution in these areas. To improve the accuracy of a solution, increasing the number of nodes within **Solid** objects which contain such singularities may be beneficial.

6.5 Troubleshooting

6.5.1 Problems Giving Solutions That Appear Incorrect

On occasion LimitState:SLAB can find a solution, with an accompanying adequacy factor and/or collapse mechanism, that does not lie within the range of anticipated values. This can occur if the adequacy factor is inadvertently applied to parts of the problem that were not initially intended. Commonly this occurs with the adequacy factor applied to **Solids**. It is worth checking that the adequacy factor is applied as required by examining the **Diagnostics** or by interrogating each solid and checking the setting in the **PE** (see Section 3.9). The settings for all solids can be checked by selecting them all and then selecting Solids in the **PE**.

In some circumstances the problem may relate to the issue of adequacy direction (see Section 6.2.6).

Part IV

User Guide

Chapter 7

Introduction to the User Guide

This part of the manual is intended to be the primary program reference guide for the use of the software.

The following aspects are described:

- The graphical user interface
- Setting up and solving a problem:
  - specifying the general project details
  - setting the grid
  - defining the model
  - generating and assigning structural properties
  - assigning boundary conditions
  - setting loads
  - setting partial factors
  - setting adequacy factor
  - solving
  - viewing and animating the solution
  - interrogating the solution
- Generating a report
- Solving multiple scenarios

The sequence listed under ‘setting up and solving a problem’ is the recommended order to follow when defining and solving a problem.

Chapter 8

The Graphical User Interface

8.1 Title Bar

The **Title bar** (as shown in Figure 8.1) runs across the top of the application window. On the left are the application icon, ***Project name*** and application name. On the right, the buttons **Minimize**, **Maximise** / **Restore Down** and **Close** may be accessed by left-clicking the relevant icons. These functions may also be accessed via the Title bar context menu by right clicking anywhere on the bar.

An asterisk (*) next to the project name signifies that the current project differs from the last saved version in some way.

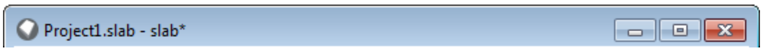


Figure 8.1: The Title Bar in LimitState:SLAB

8.2 Menu Bar

The **Menu bar** (Figure 8.2) is positioned below the Title bar and provides the user with access to the menu system and associated functions. Menu items may be selected by left-clicking. Further information about the individual menu entries is available in Appendix B.

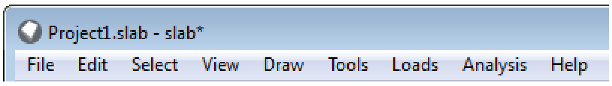


Figure 8.2: The Menu Bar in LimitState:SLAB

8.3 Toolbars

Toolbars (such as the **Show** toolbar shown in Figure 8.3) contain buttons grouped according to a common general purpose (e.g. file actions, draw actions).

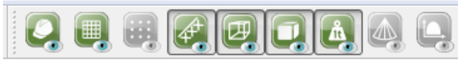


Figure 8.3: The Show toolbar in LimitState:SLAB

The action associated with a toolbar button may be activated by left-clicking with the mouse. Right clicking on any part of a toolbar brings up the explorer and toolbar selection context menu (as depicted in Figure 8.4).

Tooltips, explaining the function associated with a button, are available by hovering the mouse over a button for a short period.

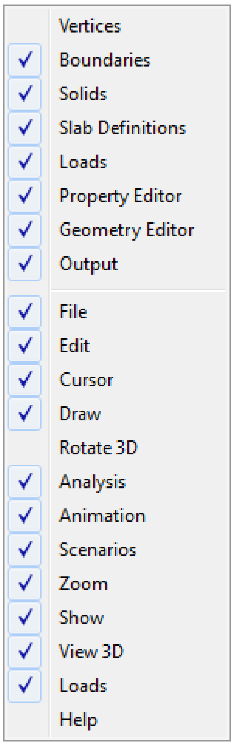


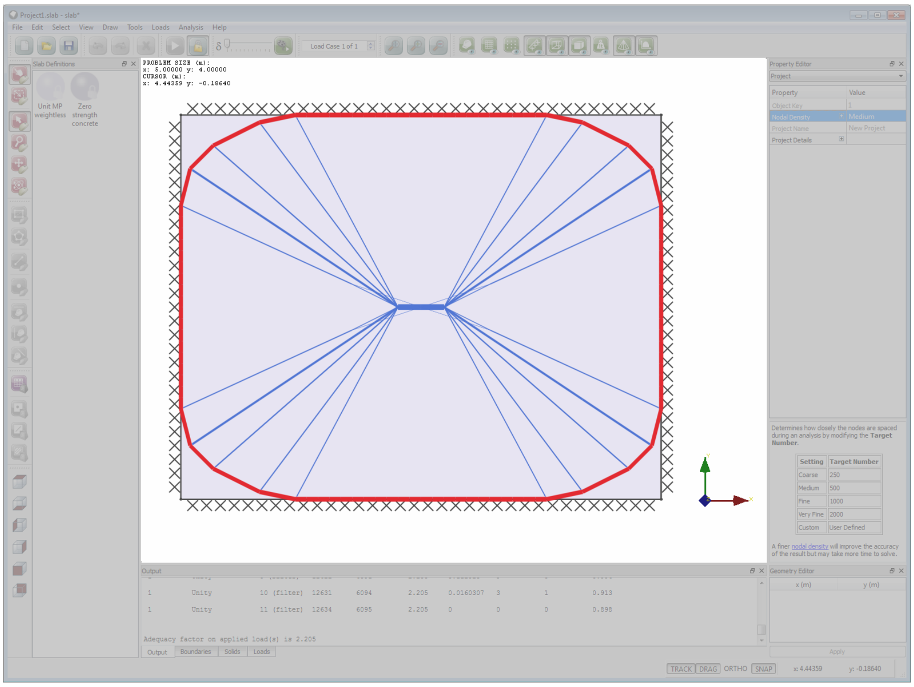
Figure 8.4: Explorer and toolbar selector

Toolbars can be added or removed from the user interface by selecting the **View menu** item, then **Toolbars**. Currently active (displayed) toolbars are marked with a tick. Highlighting and left-clicking on any of the named toolbars will toggle its status in the software (off or on).

Toolbars may also be moved around the viewer window to suit the individual preferences of the user. To do this, hover over the end of the toolbar in the viewer (usually signified by a series of dots). The cursor will change to become a four-pointed arrow (the **move** cursor). Click and hold with the left mouse button, then drag the toolbar to the required position. Releasing the mouse button will drop the toolbar in the current position.

8.4 Viewer Pane

The viewer pane (as depicted in Figure 8.5) displays the current problem geometry. It is fully interactive, providing the user with access to editable geometry objects, allowing quick and easy modification of both their shape and constituent properties.



```
PROBLEM SIZE (m):
x: 5.00000 y: 4.00000
CURSOR (m):
x: 4.44359 y: -0.18640
```

Property Editor

Project

Property	Value
Object Key	1
Nodal Density	Medium
Project Name	New Project
Project Details	

Determines how closely the nodes are spaced during an analysis by modifying the **Target Number.**

Setting	Target Number
Coarse	250
Medium	500
Fine	1000
Very Fine	2000
Custom	User Defined

A finer nodal density will improve the accuracy of the result but may take more time to solve.

Geometry Editor

x (m)	y (m)

```
1          Unity         10 (filter)  12631    6094       2.205    0.0160307  3        1         0.913
1          Unity         11 (filter)  12634    6095       2.205    0          0        0         0.898

Adequacy factor on applied load(s) is 2.205
```

x: 4.44359 y: -0.18640

Figure 8.5: The Viewer pane in LimitState:SLAB

The geometry of each object can generally be modified by selecting and dragging a **vertex**, **boundary** or **solid**. Alternatively, the **Geometry Editor** provides the means to define an object's geometry in a more precise fashion (see Section 8.6).

After selection by left-clicking with the mouse; the main object properties are displayed in the **Property Editor** (Section 8.5).

The viewer pane also includes information on the problem size and cursor position in the top left corner.

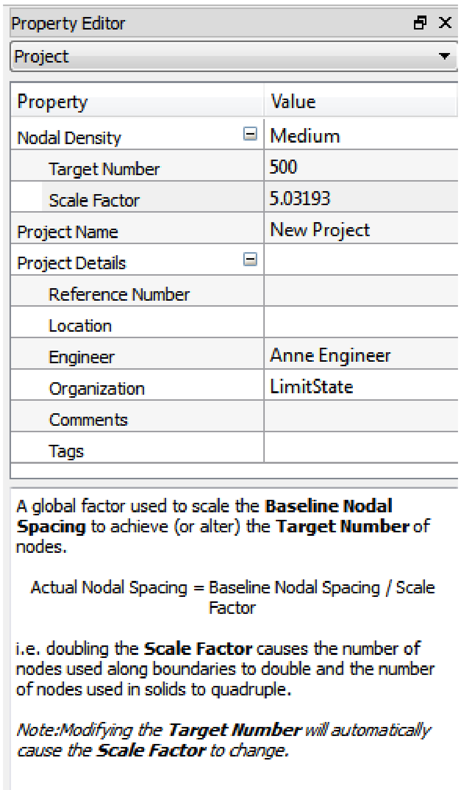
8.5 Property Editor

The **Property Editor** provides core access to problem parameters in a direct and intuitive way. In general the properties of any material or geometry object may be displayed simply by selecting it in an **Explorer** or the **Viewer** pane. In addition, global project level parameters may be displayed at any time by left-clicking on an empty part of the **Viewer** pane with the mouse. The **Property Editor** is shown in Figure 8.6.

Clicking any item in the **Property** column of the **Property Editor** gives an expanded explanation of the parameter in the window at the base of the **Property Editor**. In turn this expanded explanation may contain one or more hyperlinks to the manual to take the user to a more comprehensive source of information. A ⊞ symbol next to an item in the **Property Editor** indicates that there are additional sub-parameters relating to that item, that may be viewed. Click on the ⊞ symbol to access these. Left-clicking on a value in the **Property Editor** allows you to modify it by typing or selecting your choice (unless it is read only, in which case the text will be gray rather than black). For specific parameters, a clickable button may also appear which gives access to a further dialog to provide additional functionality.

The **calculator** (see Section 8.10) may be used in any numeric data entry cell.

Right clicking on selected items brings up a context menu relevant to that item.



Property	Value
Nodal Density ⊟	Medium
Target Number	500
Scale Factor	5.03193
Project Name	New Project
Project Details ⊟	
Reference Number	
Location	
Engineer	Anne Engineer
Organization	LimitState
Comments	
Tags	

A global factor used to scale the **Baseline Nodal Spacing** to achieve (or alter) the **Target Number** of nodes.

Actual Nodal Spacing = Baseline Nodal Spacing / Scale Factor

i.e. doubling the **Scale Factor** causes the number of nodes used along boundaries to double and the number of nodes used in solids to quadruple.

*Note:Modifying the **Target Number** will automatically cause the **Scale Factor** to change.*

Figure 8.6: Project properties displayed in the Property Editor

8.6 Geometry Editor

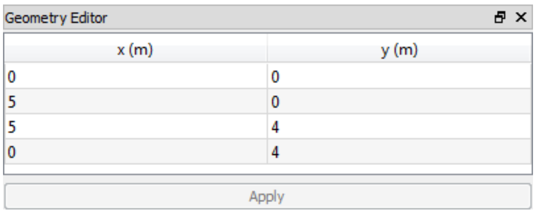
The **Geometry Editor** provides direct access to the co-ordinates of any geometry object. When a geometry object is selected for example by left-clicking on it, the **Geometry Editor** displays the coordinate of each vertex associated with that object. Any value may be altered by clicking on the value, typing in a new value and pressing enter. The arrow keys may also be used to navigate through the coordinates.

When all new parameters have been entered to the user's satisfaction, the **Apply** button should be clicked to apply the new coordinates to the selected geometry object.

Right clicking on items that have been selected brings up a context menu relevant to that item.

Any or all values may be selected and copied and pasted to another application (e.g. a spreadsheet). Conversely a table of coordinates may be copied and pasted from another application to the geometry table. To copy, select any rectangular block of data (i.e. single cell, column, row or block of cells) and then right-click with the mouse to display the context menu. Then select **Copy**.

To paste data, copy one or more cells from another application and **Paste** to a cell in the geometry editor. The data will be pasted relative to this cell. Any data extending beyond the bounds of the geometry editor table will be ignored.

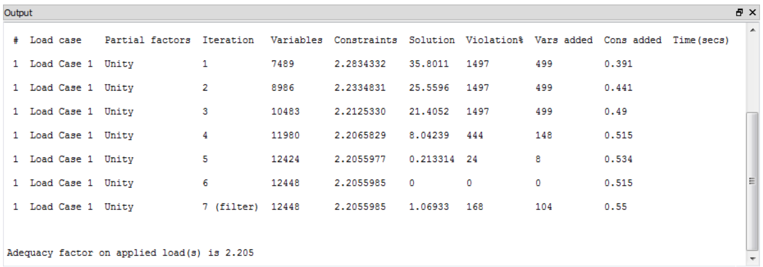


x (m)	y (m)
0	0
5	0
5	4
0	4

Figure 8.7: Polygon properties displayed in the Geometry Editor

8.7 Output Pane

The **Output pane** (as shown in Figure 8.8) is used to display messages concerning the model and solution information to the user.



```
#  Load case    Partial factors  Iteration    Variables  Constraints  Solution  Violation%  Vars added  Cons added  Time(secs)
1  Load Case 1  Unity            1            7489       2.2834332    35.8011   1497        499         0.391
1  Load Case 1  Unity            2            8986       2.2334831    25.5596   1497        499         0.441
1  Load Case 1  Unity            3            10483      2.2125330    21.4052   1497        499         0.49
1  Load Case 1  Unity            4            11980      2.2065829    8.04239   444         148         0.515
1  Load Case 1  Unity            5            12424      2.2055977    0.213314  24          8           0.534
1  Load Case 1  Unity            6            12448      2.2055985    0         0           0           0.515
1  Load Case 1  Unity            7 (filter)   12448      2.2055985    1.06933   168         104         0.55

Adequacy factor on applied load(s) is 2.205
```

Figure 8.8: The LimitState:SLAB Output Pane

Any portion of text may be copied and pasted to another window / text box or other application. To select text, perform the following steps:

- left-click on the text and drag with the mouse to select a specific block of text,

- double click on a word to select it,
- triple click on a line to select it.

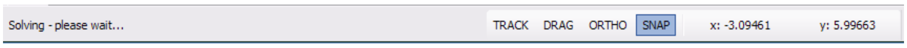
To copy, press CTRL-C or right click and select **Copy** from the context menu.

Right clicking anywhere on the window, brings up the context menu.

8.8 Status Bar

The **Status Bar** (as shown in Figure 8.8) is located at the bottom of the window and is used to provide:

- Short term progress messages to the user.
- Drawing settings (described further in Section 14.5, and Section 14.6):
  - TRACK
  - DRAG
  - ORTHO
  - SNAP
- display of the coordinates of the current mouse position, when the mouse pointer is within the **Viewer** pane.



Solving - please wait...

x: -3.09461 y: 5.99663

Figure 8.9: The LimitState:SLAB Status bar

8.9 Explorers

8.9.1 Slab Definition Explorer

The **Slab Definitions Explorer** pane (Figure 8.10) displays the slab definitions currently available to the user and provides the facility to generate more definitions or delete as required.

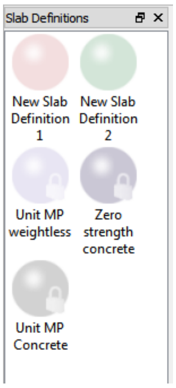


Figure 8.10: The LimitState:SLAB Structural Objects Explorer

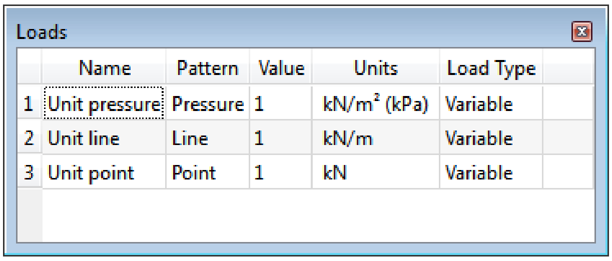
Two styles of object are available: ***pre-defined*** (read only) and ***user defined*** (editable). The user defined slab definitions are displayed at the top of the explorer window and the pre-defined objects are signified with a padlock at the bottom right corner of the corresponding icon.

The following actions are possible:

- Slab definitions may be selected by clicking on their icon with the left mouse button. When selected, the properties of the structural object appear in the **Property Editor** (Section 8.5).
- Slab definitions may be dragged and dropped on to objects in the **Viewer** pane by clicking on them with the left mouse button and then, with this button held down, dragging them with the mouse to the required location. For further information see Section 15.4.
- Right-clicking on a pre-selected slab definition brings up a context menu, which enables the user to:
  - ***Delete user defined slab definition...*** (only available for user-defined objects)
  - ***Duplicate slab definition...*** (for manual editing afterwards)
  - Create a ***New slab definition...***
  - ***Export slab definitions...*** (for use in other projects)
  - ***Import slab definitions...***
- Right-clicking elsewhere in the explorer window brings up the general context menu.

8.9.2 Loads Explorer

The **Loads Explorer** (Figure 8.11) is a read-only dialog that lists the different loads present in the **Loads Database** (i.e. those that are available for use within the project). It is displayed by default as a tab alongside the **Output Pane** , **Boundaries** and **Solids** explorers.


Loads

	Name	Pattern	Value	Units	Load Type
1	Unit pressure	Pressure	1	kN/m² (kPa)	Variable
2	Unit line	Line	1	kN/m	Variable
3	Unit point	Point	1	kN	Variable

Figure 8.11: The Loads Explorer

Information available in the **Loads Explorer** consists of:

Name The name of the load

Pattern The type of load (i.e. *Pressure*, *Line* or *Point*)

Value The magnitude of the load

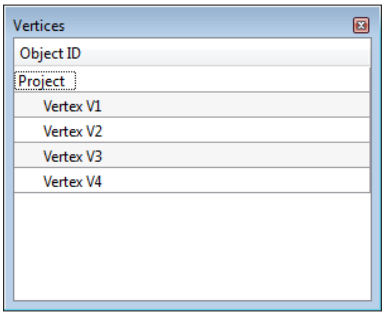
Units The units of the load (displayed as metric or imperial, depending upon the units system in force)

Load Type Either *Permanent*, *Variable* or *Accidental* (Section 6.3.2)

8.9.3 Vertex Explorer

The **Vertex Explorer** (Figure 8.12) lists the **Vertices** present in the problem. If the TRACK setting is active (see Section 8.8), clicking on a row in the explorer will select that vertex and cause the viewer to zoom in on it. Additionally, the **Geometry Editor** will display the coordinates of the selected object.

The **Vertex Explorer** is not displayed by default, but may be activated using the **View** >**Explorers** >**Vertex Explorer** menu function.


Vertices

Object ID
Project
Vertex V1
Vertex V2
Vertex V3
Vertex V4

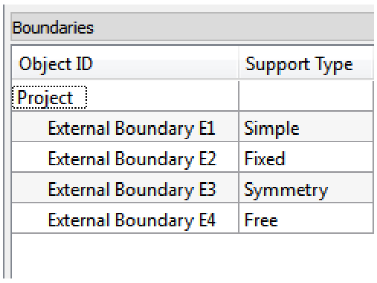
Figure 8.12: The Vertex Explorer

8.9.4 Boundary Explorer

The **Boundary Explorer** (see Figure 8.13) is displayed by default as a tab alongside the **Output Pane** , **Solids** and **Loads** explorers. It lists all the **Boundaries** present in the problem and can be used to quickly determine or modify the following properties:

Support Type *Free*, *Fixed* , *Simple* or *Symmetry* (see Chapter 16).

If the TRACK setting is active (see Section 8.8), clicking on a row in the explorer will select that boundary and cause the viewer to zoom in on it.



Boundaries

Object ID	Support Type
Project	
External Boundary E1	Simple
External Boundary E2	Fixed
External Boundary E3	Symmetry
External Boundary E4	Free

Figure 8.13: The LimitState:SLAB Boundary Explorer

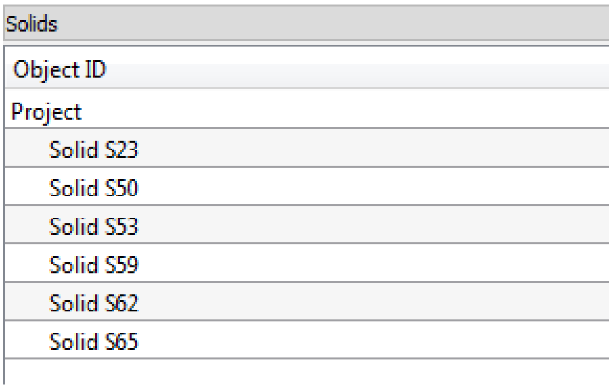
8.9.5 Solids Explorer

The **Solids** explorer (see Figure 8.14) is displayed by default as a tab alongside the **Output Pane** and **Boundaries** and **Loads** explorers. It lists the **Solids** present in the problem and can be used to quickly determine or modify the following properties

Adequacy *True* or *False* (see Section 6.2). This is applied to the self-weight of the material contained within the solid

Loading Type *Favourable*, *Unfavourable* or *Neutral* (see Section 6.3.2).

If the TRACK setting is active (see Section 8.8), clicking on a row in the explorer will select that solid and cause the viewer to zoom in on it.



Solids

Object ID

Project

- Solid S23
- Solid S50
- Solid S53
- Solid S59
- Solid S62
- Solid S65

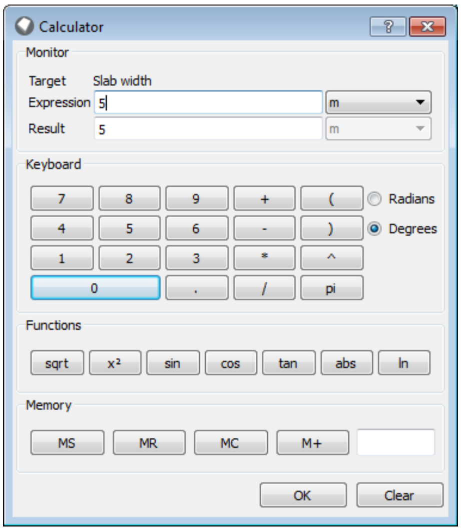
Figure 8.14: The LimitState:SLAB Solid Explorer

8.10 Calculator

The calculator is used to facilitate entry of data into the **Property Editor** and the Wizards in the following circumstances:

- When the parameter needs computing from several source parameters.
- When the parameter needs to be converted from different units.

If the mouse is clicked on any wizard or **Property Editor** numeric data entry cell, the calculator button ▦ appears in the right hand end of the cell. Click on this to display the calculator. The calculator (Figure 8.15) has all the normal functionality of a standard calculator plus the ability to convert units. The units conversions are displayed according to the parameter type in the cell. The value appearing the results window of the calculator automatically appears in the data entry cell. There is no need to copy and paste to the cell in question.



Calculator

Monitor

Target: Slab width

Expression: 5 — m

Result: 5 — m

○ Radians
● Degrees

Figure 8.15: The LimitState:SLAB calculator

Chapter 9

Opening and Saving Projects

9.1 Opening and Saving Projects

The standard load and save functions are available under the **File** menu:

Save This saves the file in the default directory using the current name. If a name has not been specified by the user then a default name: ‘Project$n$’ is used where n is set to 1 unless this name already exists in which case it is set to 1 more than the largest existing value. The Save function may also be accessed using the 💾 toolbar button.

Save as... The user is prompted for a filename and may also change the directory if required.

Open... The user is prompted to select a file from the default directory. This directory may be changed if required. The Open function may also be accessed using the 📂 toolbar button.

9.2 Auto-Recovery Files

LimitState:SLAB saves auto-recovery files every five minutes, and also when certain actions are performed by the user. If the software does not close down properly, for example due to a power outage or a crash in LimitState:SLAB, an auto-recovery file will be available. On next startup, LimitState:SLAB will inform the user that a recovery file is available, and ask whether to load it. If the user does not recover the file, it will be deleted.

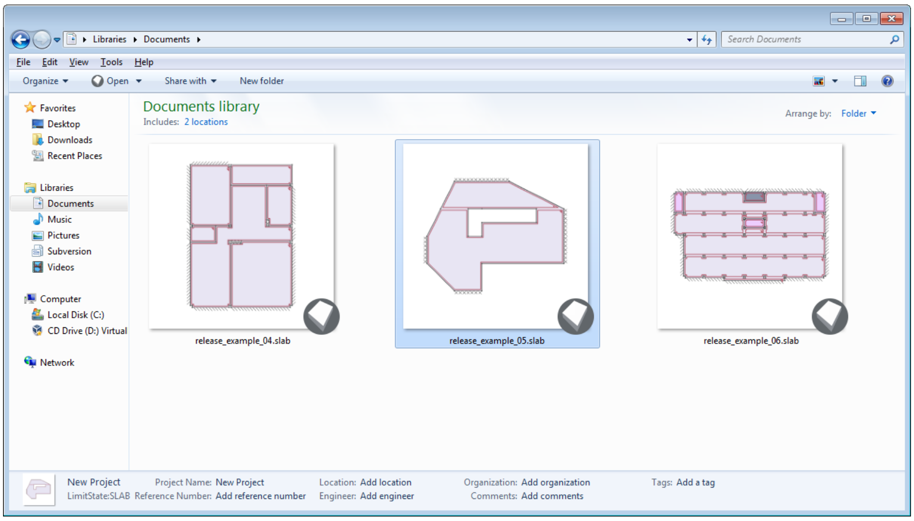
While generating auto-recovery files, a message appears in the status bar and the user is temporarily blocked from making changes to the current project.

Chapter 10

Thumbnails, Tags and Searching

10.1 Thumbnails

LimitState:SLAB will take a snapshot of the model geometry when saving the file and display this instead of the icon when navigating folders (note that this functionality may need to be enabled - see Section 2.1.1.1 for instructions on how to do this)[1]. Figure 10.1 shows an example of a folder containing three LimitState:SLAB files:



New Project
LimitState:SLAB

Project Name: New Project
Reference Number: Add reference number
Location: Add location
Engineer: Add engineer
Organization: Add organization
Comments: Add comments
Tags: Add a tag

Figure 10.1: Thumbnails and tags are saved with the LimitState:SLAB project file.

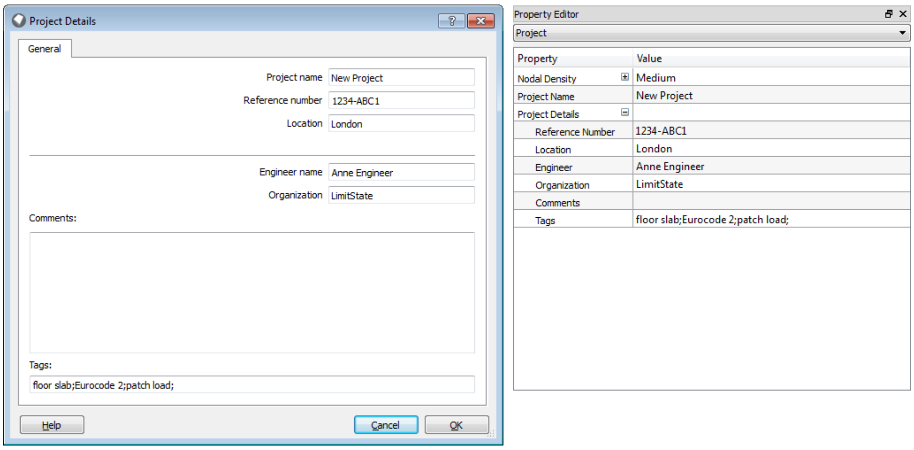
[1] Windows Vista and newer operating systems only

10.2 Tags and Searching

10.2.1 Tags

Tags (or keywords) allow the user to categorize a file and search for it on their Windows system[2] at a later date without necessarily having to open it and inspect the properties.

Tags can be edited within LimitState:SLAB either within the **Project Details** dialog or within the **Property Editor** at ***Project*** level (Figure 10.2).



Project name: New Project
Reference number: 1234-ABC1
Location: London
Engineer name: Anne Engineer
Organization: LimitState
Comments:
Tags:
floor slab;Eurocode 2;patch load;

Property	Value
Nodal Density ⊞	Medium
Project Name	New Project
Project Details ⊟	
Reference Number	1234-ABC1
Location	London
Engineer	Anne Engineer
Organization	LimitState
Comments	
Tags	floor slab;Eurocode 2;patch load;

Figure 10.2: Tags specified within the LimitState:SLAB **Project Details** dialog and **Property Editor**

Each tag in the ***Tags*** field should be separated by a semi-colon (automatically generated). For example, in Figure 10.2 the tags ”*floor slab; Eurocode 2; patch load;*” are specified. These are saved with the file and the individual words will register in a search of the system.

The tags for a project can also be edited outside LimitState:SLAB by either:

- Selecting a file and clicking in the ”Tags” field at the base of an Explorer window (selecting to **Save** once editing is complete), or
- Right-clicking the project file, selecting **Properties** and clicking the **Tags** field on the **Details** Tab.

10.2.2 Searching

To search for a LimitState:SLAB file by name, simply type some or all of the name into the Windows search box (ensuring you are in an appropriate directory). Remember to suffix the ”.slab” file extension.

To search for a tag within a LimitState:SLAB file, append the ”*tags:*” prefix to any term in the search box (e.g. search for ”*tags:drained*”).

[2] Windows 7 or above

To search for a file with specific project details (e.g. Location, Engineer or Organization) it may be necessary to first configure your system to allow file content to be searched. Details on how to do this are given in Section 2.1.1.2. Once this has been done, simply enter the appropriate terms in the search box.

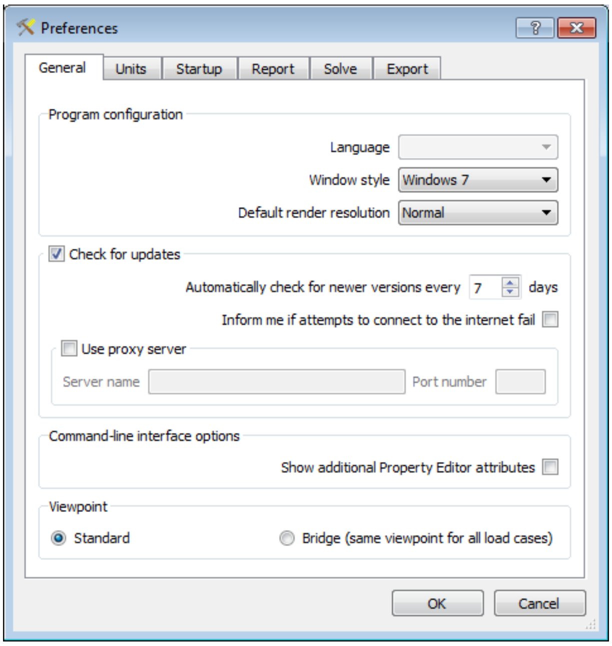
Chapter 11

Preferences

The **Preferences** dialog, available from the **Tools** menu, allows a number of LimitState:SLAB parameters to be set and saved for each time it is re-started.

11.1 General

The ***General*** Preferences tab (Figure 11.1) provides the ability to modify the language and look of the program. It also allows the user to define how the software checks for updates.



Program configuration

Language

Window style Windows 7

Default render resolution Normal

☑ Check for updates

Automatically check for newer versions every 7 days

Inform me if attempts to connect to the internet fail □

□ Use proxy server

Server name Port number

Command-line interface options

Show additional Property Editor attributes □

Viewpoint

● Standard ○ Bridge (same viewpoint for all load cases)

Figure 11.1: The **General** preferences tab

Language Change the language used by the software.

Window style Change the appearance of the software interface.

Default display render resolution Set the quality of the on-screen rendering.

Check for updates Uncheck this to prevent the software from periodically checking for newer versions.

Automatically check for newer versions every X days Use the up and down arrows to set the length of time between checks.

Inform me if attempts to connect to the internet fail Check this to be alerted if update checks are not successful.

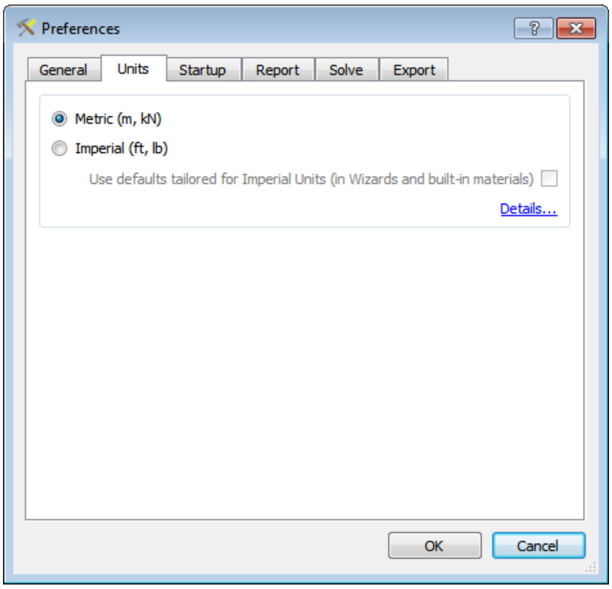
Use Proxy Server Check this option to use a proxy server as the gateway for update checks (server name and port number required).

Show additional Property Editor attributes Check this option to display the unique object 'key' for each object in the **Property Editor**.

Viewpoint Select ***Standard*** to allow the camera position to shift when switching between animated solutions for different Load Cases. Alternatively, select ***Bridge*** to keep the same camera viewpoint. This may e.g. prevent 'jumping' when viewing different mechanisms caused by a vehicle load traversing across a bridge slab.

11.2 Units

The ***Units*** tab (Figure 11.2) provides the ability to toggle between *Metric* and *Imperial* units systems. If *Imperial* units are selected, the user has a further option to use default values that have been rounded appropriately for ease of use.

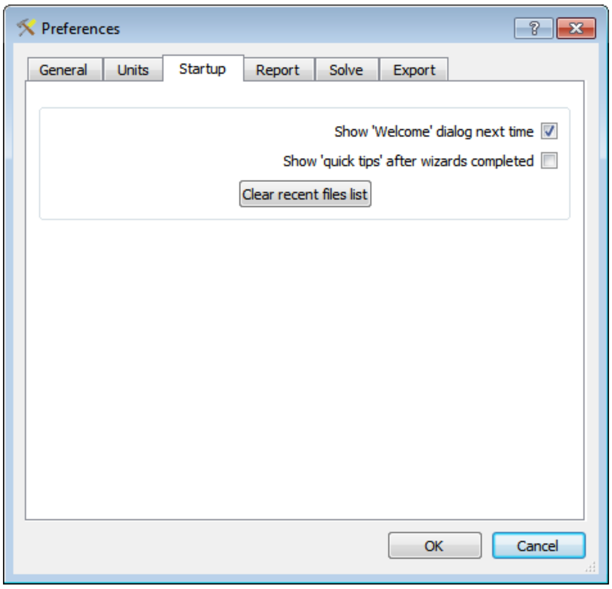


● Metric (m, kN)
○ Imperial (ft, lb)
Use defaults tailored for Imperial Units (in Wizards and built-in materials) □

Figure 11.2: The **Units** preferences tab

11.3 Startup

The ***Startup*** Preferences tab (Figure 11.3) provides the ability to modify the features presented to the user each time the program is started.



Show 'Welcome' dialog next time ☑

Show 'quick tips' after wizards completed □

Figure 11.3: The **Startup** preferences tab

Show 'Welcome' dialog next time Display the welcome screen at startup. If this is deselected, the software will start without offering a choice of Wizard to the user.

Show 'Quick Tips' after wizards completed Check this to be provided with a dialog of useful information after completing a Wizard.

Clear Recent Files List Click this button to clear the recent files list (found under the **File** menu).

11.4 Report

The ***Report Preferences*** tab (Figure 11.4) allows the user to set the default header and footer images used in the report.

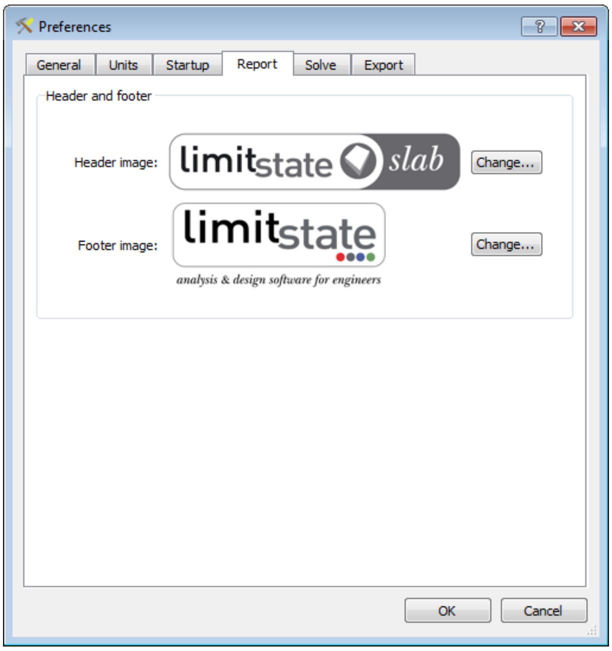


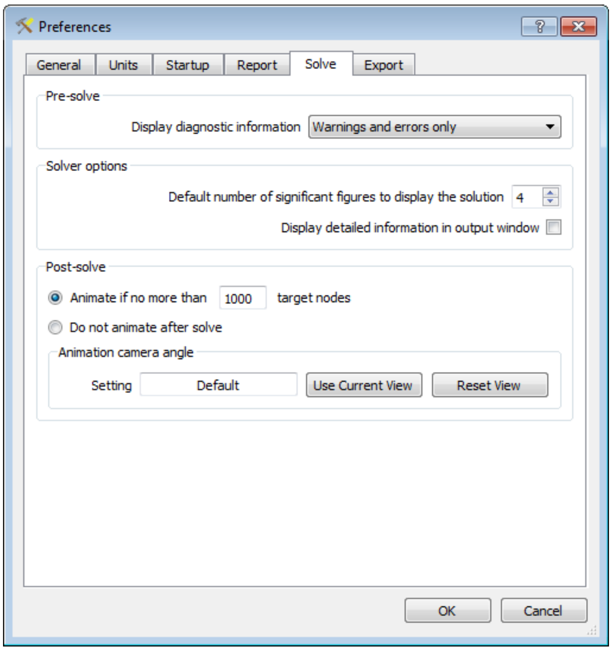
Figure 11.4: The **Report** preferences tab

Header image Click the ***Change...*** button to select a new PNG image to use at the head of the report.

Footer image Click the ***Change...*** button to select a new PNG image to use at the foot of the report

11.5 Solve

The ***Solve*** Preferences tab (Figure 11.5) allows the user to set when the pre-solve **Diagnostics** dialog is displayed and alter the solution information that is presented in the **Output Pane**.



Pre-solve

Display diagnostic information: Warnings and errors only

Solver options

Default number of significant figures to display the solution: 4

Display detailed information in output window □

Post-solve

● Animate if no more than 1000 target nodes

○ Do not animate after solve

Animation camera angle

Setting: Default

Figure 11.5: The **Solve** preferences tab

Display diagnostic information Use the drop-down list to set whether the **Diagnostic** dialog is displayed at Solve time a) *Always*, b) when there are *Warnings or Errors* or c) when there are *Errors Only*.

Default number of significant figures to display the solution Change this to alter the number of significant figures to which the **Adequacy factor** is reported in the **Output Pane** and **Report**.

Display detailed information in output window Check this box to add extra columns to the solution table in the **Output Pane**. Columns added include:

- **Iteration** - the iteration number.
- **Variables** - the number of variables in the linear programming matrix at this iteration.
- **Constraints** - the number of constraints in the linear programming matrix at this iteration.
- **Violation %** - the maximum percentage violation of the yield-line adding criterion encountered at this iteration.
- **Vars added** - the number of variables added to the linear programming matrix on this iteration.
- **Cons added** - the number of constraints added to the linear programming matrix on this iteration.
- **Time(secs)** - the time taken to solve the problem at this iteration.

Animate if no more than $\boxed{\text{X}}$ target nodes If the target number of nodes for the project is fewer than the value of X, the solution will automatically animate on completion of the solve step.

Do not animate after solve Do not animate on completion of the solve step, irrespective of the complexity of the problem.

Animation camera angle Click **Use Current View** to use the view camera angle currently selected by the user. Click **Reset View** to revert to the default settings. The current setting is displayed in the **Setting** textbox.

11.6 Export

The ***Export Preferences*** tab (Figure 11.6) allows the user to set the default size of images and animations when exported to file.

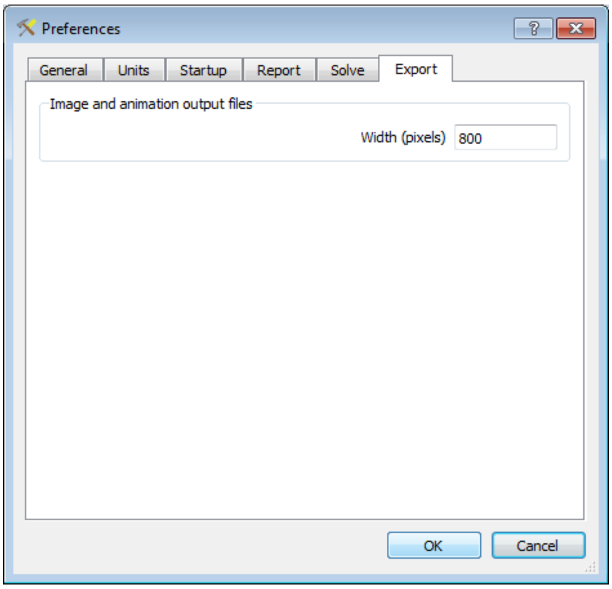


Image and animation output files

Width (pixels) 800

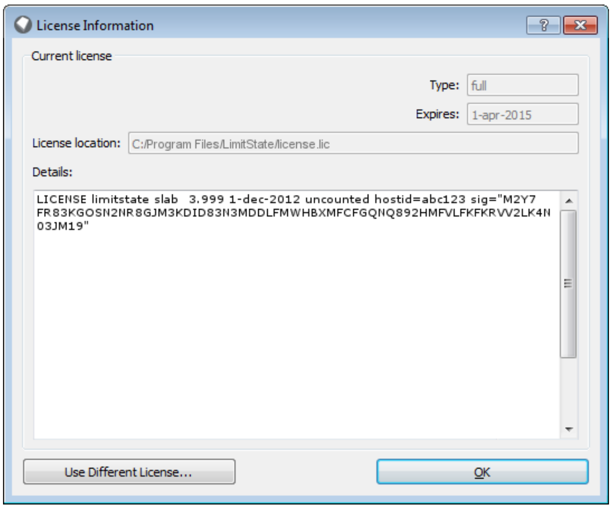
Figure 11.6: The **Export** preferences tab

Width (pixels) Controls the width of the image / animation (to a maximum width of 1200 px).

Chapter 12

License Information Dialog

The **License Information** dialog (Figure 12.1) is accessed from the **Help** menu and provides information on the license currently being used as well as the ability to swap to using a different license (e.g. as the result of an upgrade or renewal).



Type: full

Expires: 1-apr-2015

License location: C:/Program Files/LimitState/license.lic

Details:

```
LICENSE limitstate slab  3.999 1-dec-2012 uncounted hostid=abc123 sig="M2Y7
FR83KGOSN2NR8GJM3KDID83N3MDDLFMWHBXMFCFGQNQ892HMFVLFKFKRVV2LK4N
03JM19"
```

Figure 12.1: The License Information dialog

Type Describes the type of license being used (*full*, *trial*, etc.). This determines the level of functionality available.

Expires The date on which the license will cease to work.

License location The path to the license file being used.

Details The contents of the license file. This can be used to determine, amongst other things, the product, the highest version number that can be licensed, the hostid (computer identifier) and the license expiry date.

Use Different License... Click this button to disassociate from the currently used license and cause LimitState:SLAB to request a new one. This is generally used when upgrading or replacing a license file and will require the software to restart. It is advised that all work is saved before using this.

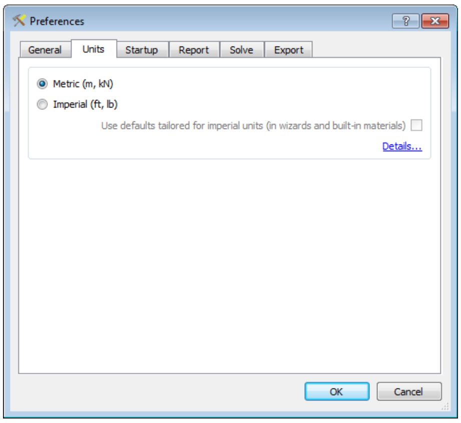
Chapter 13

Starting Out

13.1 Setting the Units

The LimitState:SLAB interface can display either Metric (kN, m) or Imperial (lb, ft) units.

To set the units used, open the ***Preferences...*** dialog in the ***Tools*** menu. Go to the ***Units*** tab and select the units that you wish to use (see Figure 13.1). Changes will take effect when LimitState:SLAB is next restarted.



● Metric (m, kN)
○ Imperial (ft, lb)
Use defaults tailored for imperial units (in wizards and built-in materials) □

Figure 13.1: Changing units in LimitState:SLAB

The default units used in each setting are given in Table 13.1.

Imperial conversions of Metric measurements can result in values with many significant figures, which can be difficult to work with. The option to use ‘tailored’ default Imperial values in the Wizards and built-in materials is therefore also provided. By selecting this option, the pre-defined values for problem geometries and material properties are rounded to an appropriate number of significant figures.

Measurement	**Metric**	**Imperial**
Length	m	ft
Area	m^2	ft^2
Volume	m^3	ft^3
Force	kN	lb
Weight	kN	lb
Force per unit width	kN/m	lb/ft
Unit weight (weight density)	kN/m^3	lb/ft^3 (pcf)
Pressure	kN/m^2 (kPa)	lb/ft^2 (psf)
Angle	degrees	degrees
Bending moment	kNm	$lb.ft$ (pf)
Bending moment per unit width	kNm/m	$lb.ft/ft$

Table 13.1: Default units used in Metric and Imperial modes

13.2 Starting with an Empty Project

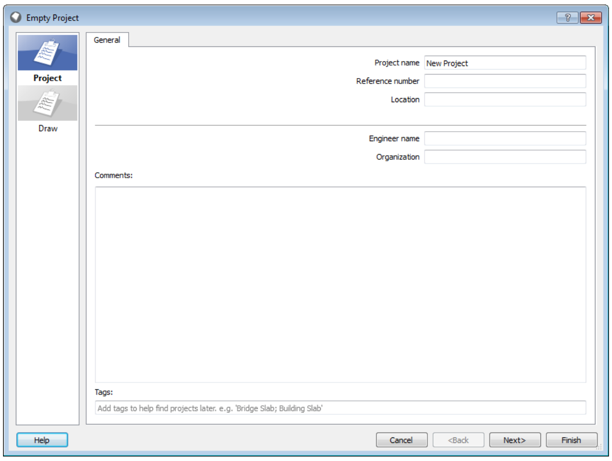
To start with an empty project, select **Create a new project** in the **Welcome to LimitState:SLAB** dialog and click **OK**, or if the software is already running, click File>New or 🗋. The **New Project** dialog will then start. Select the **Empty** project and click **OK** to display the **Empty Project** dialog shown in Figure 13.2.

13.2.1 Project Details

The first tab on the **Empty Project** dialog shown in Figure 13.2 is for the input of project data. None of the fields are mandatory, but a default name of **New Project** will be displayed and used unless changed by the user. Once all the necessary fields have been filled in, clicking **Next** will advance on to the next stage of problem definition.

13.2.2 Draw Settings

The second tab in the **Empty Project** dialog displays the options for setting up the drawing environment. It is concerned with establishing suitable snap settings to enable a model to be produced in a quick and efficient manner, especially when used in conjunction with the grid system, which is a useful aid to modelling and, when set up correctly in conjunction with the snaps, can save the user much time and effort.

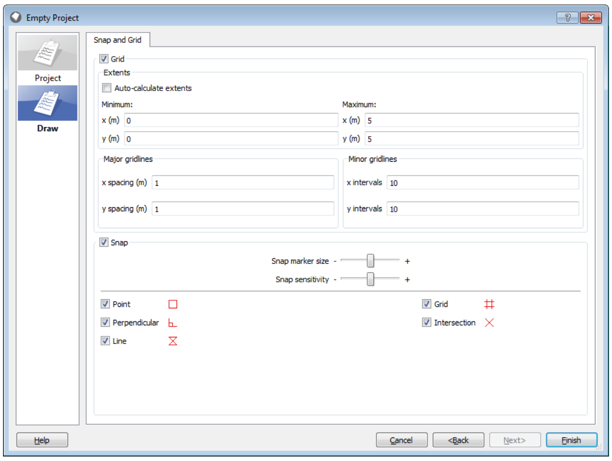


Project name: New Project
Reference number:
Location:
Engineer name:
Organization:
Comments:
Tags: Add tags to help find projects later. e.g. 'Bridge Slab; Building Slab'

Figure 13.2: The **Empty Project** dialog (**Project Details** tab)

13.2.2.1 Snap Settings

Object snap in LimitState:SLAB is very similar to that found in many CAD and drawing packages - it causes the cursor to become attracted to certain features of the model, such as points or intersections between lines.



☑ Grid
Extents
□ Auto-calculate extents
Minimum: x (m) 0, y (m) 0
Maximum: x (m) 5, y (m) 5
Major gridlines: x spacing (m) 1, y spacing (m) 1
Minor gridlines: x intervals 10, y intervals 10
☑ Snap
Snap marker size - +
Snap sensitivity - +
☑ Point
☑ Perpendicular
☑ Line
☑ Grid
☑ Intersection

Figure 13.3: The **Empty Project** dialog (**Draw Settings** tab)

To use the snap functionality from the start of modelling, simply ensure that the **Snap** check box is ticked in the **Draw Settings** tab (this is done by default). You can then fine-tune the size of the snap markers and select the type of snaps that you wish to use:

- **Snap marker size** - Use the slider to make the snap marker larger (**+**) or smaller (**-**).
- **Snap sensitivity** - This determines how close the cursor needs to be to a particular feature in order to snap to it. Use the slider to make the distance smaller (**+**) or larger (**-**).
- **Point** - Causes the cursor to snap to points (**Vertices**).
- **Perpendicular** - When drawing a line or polygon, this will cause the cursor to snap to a point on an existing line that forms a right angle between that and the line being drawn.

- **Line** - Causes the cursor to snap to line objects (**Boundaries**).
- **Grid** - Causes the cursor to snap to grid points and points of intersection between gridlines.
- **Intersection** - Causes the cursor to snap to points of intersection between the gridlines and the **Line Objects** of the model.

Clicking **Finish** will end the setup process and display the modelling environment. The grid can subsequently be adjusted and toggled on or off at any time during modelling via the **Settings** (see Section 14.5) dialog of the **Draw** menu and the icon respectively. Similarly, the snap functionality can be quickly toggled by clicking the SNAP button on the status bar.

13.3 Starting with a DXF Imported Geometry

The user may often find it useful to import a problem geometry that has already been pre-defined using a CAD package. This can be accomplished in LimitState:SLAB by using the **Import... Geometry...** function, found under the **File** menu.

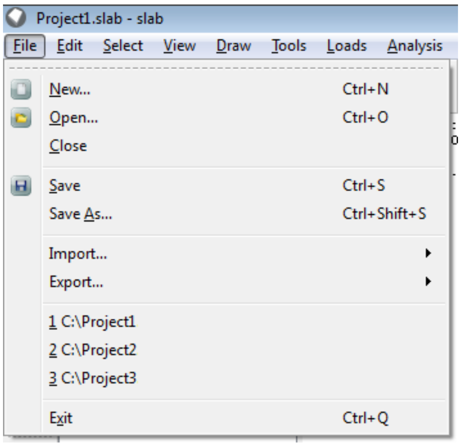


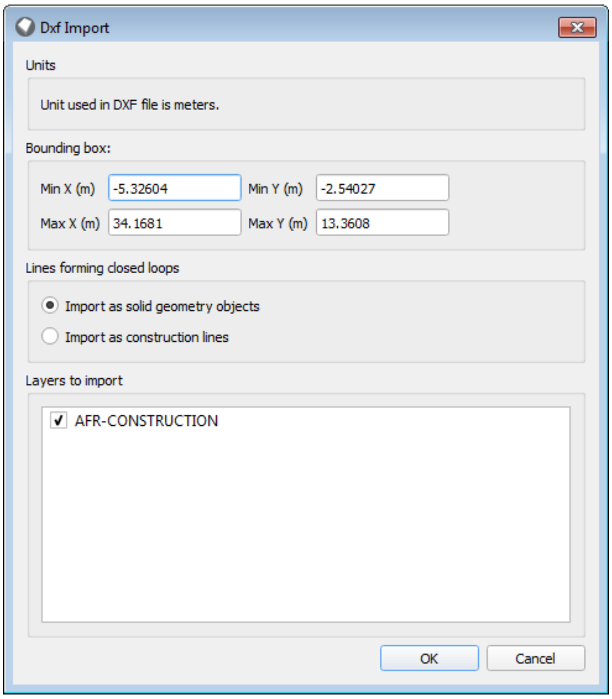
Figure 13.4: The **Import...** command in the **File** menu (6th command down).

13.3.1 Importing a DXF

To start a new project with a DXF defined geometry, simply begin with the **Empty Project** (see Section 13.2) wizard, click **Finish** then navigate to **Import... Geometry...** . Clicking this will bring up a dialog that allows you to browse for a pre-saved DXF file.

Once a DXF file has been selected, the DXF Import dialog will appear. This presents the user with a number of pieces of information as well as options:

UNITS This alerts the user to the units in which the DXF file has been saved. If the file is set as 'Unitless' or does not have a setting, the software will assume that it is the same as the default measurement setting of the interface.



Units

Unit used in DXF file is meters.

Bounding box:

Min X (m) -5.32604 Min Y (m) -2.54027

Max X (m) 34.1681 Max Y (m) 13.3608

Lines forming closed loops

● Import as solid geometry objects

○ Import as construction lines

Layers to import

☑ AFR-CONSTRUCTION

Figure 13.5: The **DXF Import Dialog**

BOUNDING BOX This provides the maximum and minimum *x* and *y* coordinates for a bounding box enclosing all the objects in the DXF. If the model appears to be excessively large, or if it is a long way from the origin, a warning will be displayed alerting the user to check the origin or scaling of the file.

HOW TO INTERPRET CLOSED LOOPS LimitState:SLAB deals with solid bodies and the interfaces between them; therefore, by default when **Import as solid geometry objects** is selected, the DXF import function recognizes lines that form a closed loop and interprets them as being a solid object (Figure 13.6). Lines that do not form a closed loop will be imported as construction lines so that the user is able to still use them when defining the model geometry. Alternatively, there is the option to interpret all lines within the DXF file as being construction lines. If the option **Import as construction lines** is selected, LimitState:SLAB solids and boundaries will not be generated and the user must draw them.

In all cases, imported DXF construction lines appear as solid grey lines in order to easily differentiate them from those defined within the program.

Where a closed loop exists within another closed loop (i.e. an ‘island’), LimitState:SLAB will attempt to generate joining lines to turn both into solid objects. Where this is not possible, a warning message (Figure 13.7) will be displayed prompting the user to manually rectify the problem and attempt import once more.

THE CHOICE OF LAYERS TO IMPORT DXF files can sometimes be composed of several layers and the user may not always wish to import all of them into their LimitState:SLAB model. All layers present in a file are listed in the DXF Import dialog; to prevent one or more from being imported, simply un-check the box next to the name of the appropriate layer (N.B. where a layer has not been given a name, ‘Unnamed Layer’ or a blank space will appear in the import dialog).

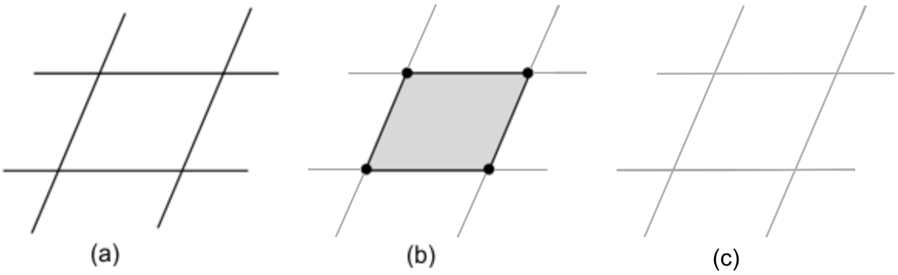
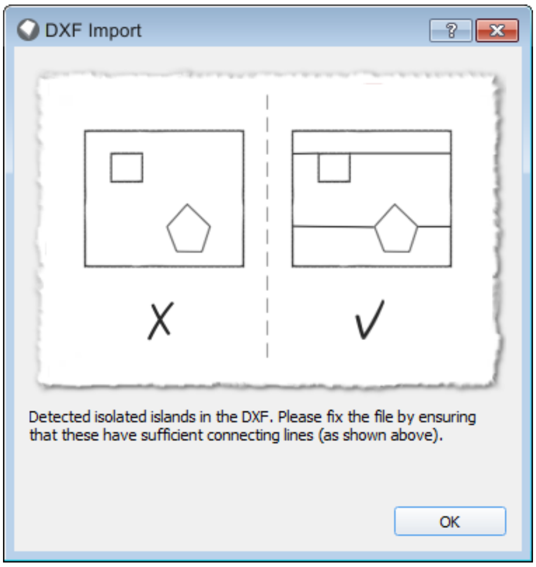


Figure 13.6: Solid object identification using DXF import: (a) Original DXF file contents, (b) Solid object, boundaries, construction lines and vertices as imported with closed loops interpreted as solid objects and (c) construction lines as imported with closed loops interpreted as construction lines.



Detected isolated islands in the DXF. Please fix the file by ensuring that these have sufficient connecting lines (as shown above).

Figure 13.7: Warning message shown when the DXF file being imported contains islands that the software is unable to process.

13.3.2 Permitted DXF Commands

The following commands can be used to create a DXF file that is readable by LimitState:SLAB (other commands, including those used to generate 3D objects, will not be recognized):

- Point
- LWPolyline
- Line
- Polyline
- XLine
- Spline
- Vertex

Closed loops of lines forming ‘islands’ within other closed loops will be recognized and imported without difficulty. However, additional lines will be automatically generated to connect these ‘islands’ to the surrounding geometry (to allow LimitState:SLAB to analyse the problem properly).

13.3.3 Tips for Modifying a DXF in an External CAD Package

Whilst working on a DXF file for import into LimitState:SLAB it is useful to bear in mind the following points:

1. ENSURE LOOPS ARE PROPERLY CLOSED

   In most CAD packages it is possible to work to a very fine precision. This can sometimes lead to situations where lines that appear to intersect do not actually meet in reality. Whilst not necessarily causing a problem in the CAD model, if two lines of a loop do not intersect when importing a DXF into LimitState:SLAB, a solid object will not be formed. Care should therefore be taken to ensure that, where objects are expected to be converted to solids, these are properly drawn in the CAD model before exporting to DXF (working with a grid or object snap turned on can help with this).

2. REMOVE UNNECESSARY OBJECTS

   Only those types of drawing object listed in Section 13.3.2 will be recognized and imported into LimitState:SLAB. If a CAD file is being worked on specifically for import into LimitState:SLAB then text, hatching and other similar objects should be removed before the DXF file is generated. Failure to do this may lead to unwanted objects being created or to a loss of program efficiency as LimitState:SLAB processes the superfluous data.

3. KEEP THE DRAWING AS SIMPLE AS POSSIBLE

   When importing from a DXF file, every intersection of two or more lines will be converted to a LimitState:SLAB vertex. These vertices are, in turn, regarded as nodes along the boundaries of solid elements at the time of analysis. As LimitState:SLAB normally works with a fixed number of nodes, excessive detail (leading to large numbers of boundary nodes) will reduce the number of nodes inside solid elements and potentially reduce the accuracy of the solution obtained. Wherever possible, the user is advised to appropriately simplify the profile of any problem before importing and try to achieve a suitable balance of boundary and internal nodes in the LimitState:SLAB model. This advice is particularly relevant when working with DXF files containing multiple layers.

4. WORK AT THE CORRECT SCALE

   LimitState:SLAB is set to work in either metres or feet (dependent upon the choice of units in the **Preferences** menu). It should therefore be ensured that all imported DXF files are drawn to an appropriate scale.

5. BE AWARE THAT LAYERS ARE FLATTENED

   Since LimitState:SLAB works with planar models, when multi-layered DXF files are imported, all layers are first flattened. Any overlapping lines that were distinct in the original file will no longer be separate, which may result in undesired problem geometries. It is recommended that such DXF files are simplified to a single layer representing the problem the user wishes to model.

6. WORK IN THE *XY* PLANE

   Care should be taken to ensure that the correct viewpoint is being used when preparing a DXF file for import. LimitState:SLAB works in the *xy* plane, which corresponds to the ‘Plan’ or ‘Top’ 3D viewpoint in most CAD packages. Objects that lie predominantly in the *xz* or *yz* planes may be imported in a way that is not desirable. It is recommended that DXF files containing 3D components are simplified to a single (2D) layer representing the problem the user wishes to model.

13.3.4 Permitted DXF Types

DXF files can be produced in either ASCII or binary format. LimitState:SLAB will only recognize those files that have ASCII encoding. It is therefore recommended that the user checks the type of any DXF file before attempting an import.

13.3.5 Following DXF Import

Following a successful DXF import, it will be necessary to apply the requisite material properties, loading and support conditions to the model before an analysis can be attempted.

13.3.6 Export to DXF

The **Export... Geometry...** command (also found in the **File** menu) will save the geometry of any LimitState:SLAB project to a suitably formatted DXF file (if the DXF filetype is selected). If the project is in a solved state, it is possible also to save the entities generated during the solution process, such as nodes and yield-lines.

13.4 Project Details

To edit the project details, on the **Tools** menu click **Project details....** Alternatively the details can be accessed in the **Property Editor** by clicking in whitespace within the **Viewer Pane**.

The following details are available to be edited, none are compulsory:

- ***Project name***
- ***Reference No.***
- ***Location***
- ***Assessor name***
- ***Assessor organization***
- ***Comments***

- ***Tags***

Chapter 14

Specifying the Problem Geometry

14.1 Terminology

Problem geometries are built up using **Geometry objects**. There are three types of geometry object:

Solid This is a 2D polygon defining a slab or portion of a slab. Its extent is defined by the surrounding **Boundary** objects.

Boundary This is a straight line that links two vertices and defines the edge or boundary of a **Solid**. If a Boundary object separates two **Solids** then it is shared by those solids and forms an interface.

Vertex This is a point where two or more **Boundary** objects meet. A vertex may lie on a straight line. A Vertex is shared by the **Boundary** objects that meet at that vertex.

In LimitState:SLAB all geometry is defined in terms of straight lines. Curves may be represented by a series of short straight line segments. **Boundary** and **Solid** objects can both be assigned material properties.

In general most geometry will be built up using the **Draw Rectangle** and **Draw Polygon** functions, as found on the Draw Toolbar. If a polygon is added adjacent to an existing polygon, LimitState:SLAB automatically ensures that each polygon shares the interface **Boundary object**.

14.2 Construction Lines

In addition to **Grids**, **construction lines** can provide a useful tool when setting up a problem geometry. These lines appear as grey lines in the viewer pane and possess the same snap functionality as the standard geometry objects but, like the grid, construction lines are not counted as part of the problem during analysis.

Construction lines can be dragged and deleted, just like standard drawing objects. In addition, to clear all of the construction lines at the same time, simply choose **Clear All Construction Lines** from the **Construction Line** section of the **Draw** menu shown in Figure 14.1.

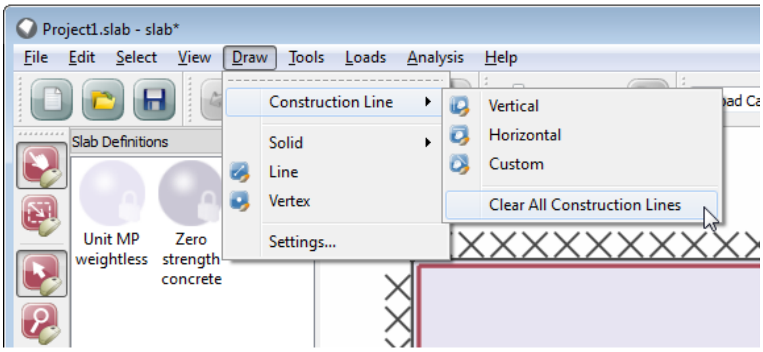
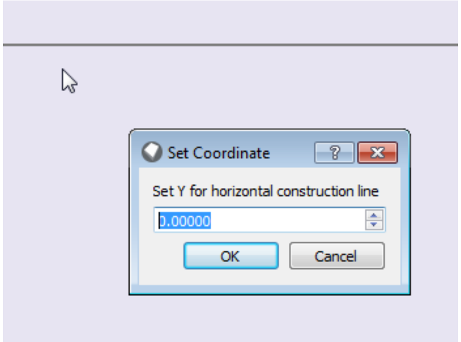


Figure 14.1: Clearing construction lines

There are three types of construction line available: **Horizontal**, **Vertical** and **Custom** (angled):

14.2.1 Horizontal Construction Lines

To draw a horizontal construction line, click the button in the toolbar. When hovering over the **Viewer Pane**, the cursor will be accompanied by a solid, horizontal black line that denotes the current position of the construction line; to place this in an approximate position, simply use the cursor position to choose an appropriate *y* coordinate and left-click the mouse. For a more accurate positioning, right-click the mouse and choose the **Set *y* coordinate** option. A dialog will then appear that allows a precise *y* coordinate to be entered (see Figure 14.2). The option to continue placing construction lines will remain until the user presses the **ESC** button on the keyboard or right-clicks the mouse and chooses the **Cancel** option.



Set Y for horizontal construction line

0.00000

Figure 14.2: Setting the y position of a horizontal construction line

14.2.2 Vertical Construction Lines

To draw a vertical construction line, click the button in the toolbar. The procedures for adding vertical construction lines are the same as for adding horizontal construction lines except that the *x* coordinate is now set instead of the *y*.

14.2.3 Custom Construction Lines

To draw a custom (angled) construction line, click the button in the toolbar. The next left click of the mouse will then set the first point of the construction line - this will be taken as the origin of rotation. Alternately, right-click the mouse and choose **Add point** to set the origin more precisely.

A solid black line will now appear that rotates around the origin point with any movement of the cursor. To set the angle by specifying a second point, simply left-click the mouse in the **Viewing Pane** or right-click and choose **Add point** to set the destination more precisely. Should it be necessary to enter an angle of rotation instead of a second point, right-click the mouse and choose the **Set angle** option. A dialog will then appear that allows an angle (in degrees) to be entered. This is measured around the origin point, from the horizontal axis in an anti-clockwise direction.

Note: Custom construction lines are a useful tool when extending geometries that include angled **Boundaries** that you do not wish to move in the direction of the extension:

1. Draw an angled **Custom Construction Line** along the boundary that you wish to retain.

2. Adjust the boundaries / geometry of the project as required.

3. Select and hold the **Vertex** at one end of the displaced **Boundary** you wish to retain. Move it to an appropriate position on the **Custom Construction Line** (e.g. an intersection with another **Boundary**). Repeat as necessary.

14.2.4 Deleting Construction Lines

Construction lines can be selected individually or as a group and then deleted (as with most objects). To do this, use either the **Click**, or **Rectangle** select tools to select the relevant construction lines then press **DEL** or click the **Delete button** .

14.3 Drawing Functions

14.3.1 Rectangle

Click on the toolbar button , or from the menu select **Draw**, **Rectangle.** Left click with the mouse anywhere on the geometry window and then with the mouse button held down, drag a rectangle as shown in Figure 14.3.

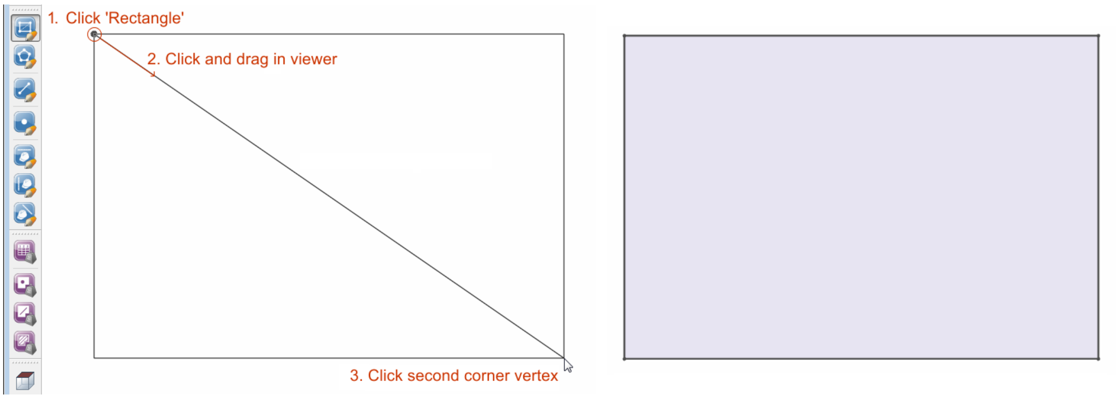


Figure 14.3: Drawing a rectangle

14.3.2 Polygon

Click on the toolbar button, or from the menu, select **Draw**, **Polygon**. Left click with the mouse anywhere on the geometry window to draw the first vertex of the polygon. Then move the mouse to the position of the next vertex and left click to draw this. Continue clicking until all vertices of the polygon have been drawn. To complete the polygon, click again on the first vertex, or right-click to display the context menu and select **Finish**. This will connect the last vertex drawn to the first vertex.

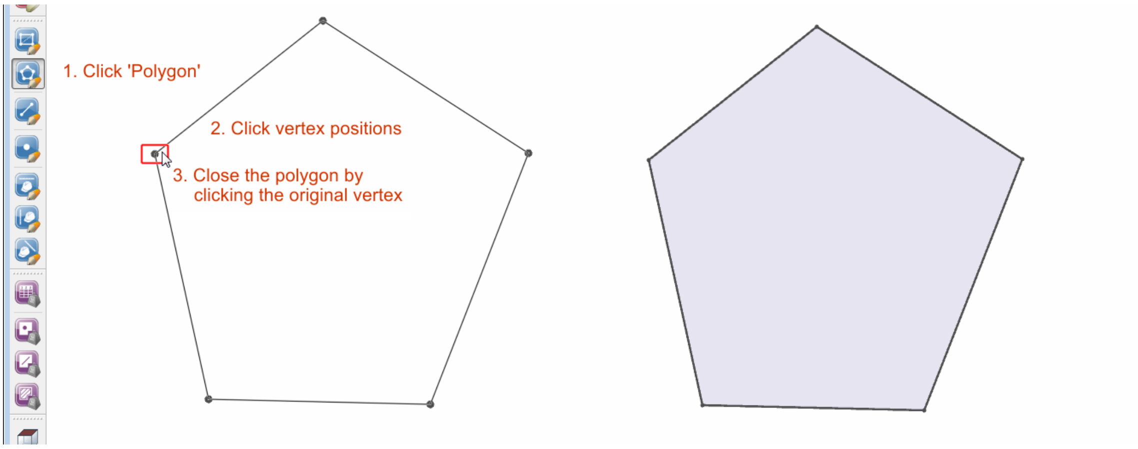

1. Click 'Polygon'
2. Click vertex positions
3. Close the polygon by clicking the original vertex

Figure 14.4: Drawing a polygon

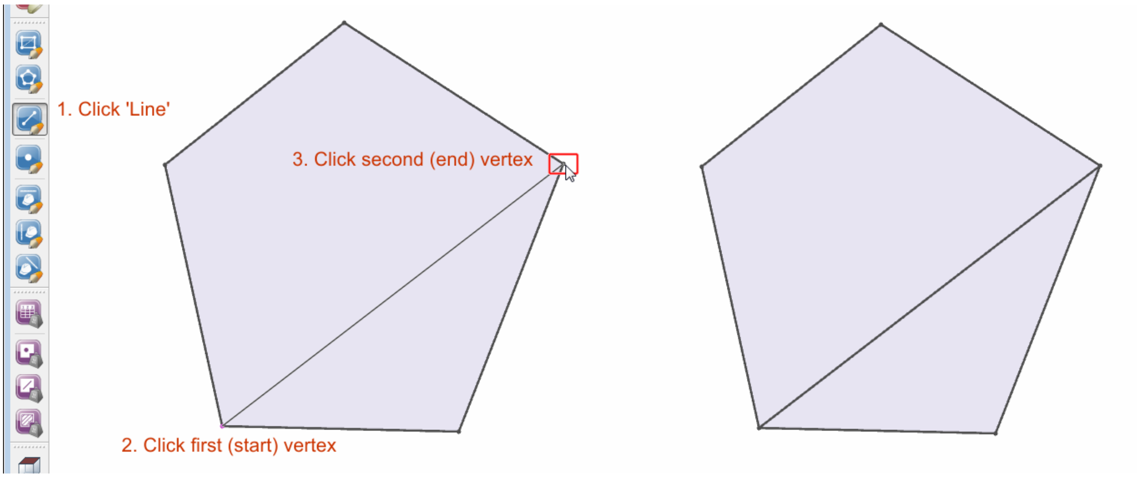
To exit from drawing the polygon and clear the currently drawn vertices, press ESC.

When drawing a **Polygon**, it is permissible to utilize existing **Vertex objects** (or even **Boundaries**) as part of the polygon. LimitState:SLAB can be set to snap to existing geometry objects to facilitate this (see Section 14.5). This is the normal way in which polygons are added adjacent to existing polygons.

14.3.3 Line

Lines (**Boundary objects**) are not allowed to exist in isolation in LimitState:SLAB and are used to split existing **Solid objects**. To draw a line, click on the toolbar button , or from the menu, select **Draw**, **Line**. Now left-click on any existing **Line** or **Vertex** and then using the mouse connect it to another **Line** or **Vertex** by clicking on it. The **Line** so drawn must pass across an existing **Solid object** as shown in Figure 14.5. If this is not the case then a warning message is displayed. If the line is legitimate then a message appears in the output pane stating that the **Solid object** has been split.

When a **Line** is drawn from a point on one **Line** to a point on another across an existing **Solid object**, additional **Vertices** will automatically be created where required.


1. Click 'Line'

3. Click second (end) vertex

2. Click first (start) vertex

Figure 14.5: Drawing a line

14.3.4 Vertex

Vertex objects may be used to split existing **Boundaries**. To add a **Vertex**, click on the toolbar button , or from the menu, select **Draw**, **Vertex** and left-click on any existing **Boundary**. If the vertex is legitimate then a message appears in the output pane stating that the boundary has been split.

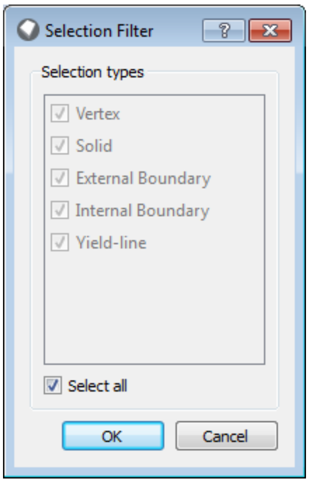
14.4 Selecting Objects

14.4.1 Single Click Selection

Single selection mode may be activated by using the toolbar buttons 'Select' and 'Click' . In this mode any object may be selected by clicking on it with the mouse. As soon as it is selected it will be highlighted and its properties will appear in the **Property Editor**. If it is a **Geometry Object**, then its coordinates will also appear in the **Geometry Editor**.

14.4.2 Rectangle Selection

Rectangle selection mode may be activated by activating the toolbar buttons ‘Select’ and ‘Rectangle’ . In this mode any object or set of objects may be selected by dragging a rectangle around them with the mouse. When dragging from left to right, the rectangle is red and must fully enclose the required items. When dragging from right to left, the rectangle is green and any objects that the rectangle encloses or touches will be selected. As soon as they are selected, objects will be highlighted and common properties shared by all the selected items will appear in the **Property Editor**. To select only specific types of objects, use the **Selection Filter** dialog (Figure 14.7) from the main menu (**Select** - **Filter...**).


Selection Filter

Selection types

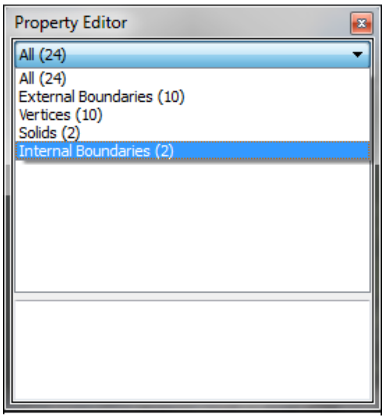
☑ Vertex
☑ Solid
☑ External Boundary
☑ Internal Boundary
☑ Yield-line

☑ Select all

OK Cancel

Figure 14.6: The Selection Filter dialog

Alternatively when multiple objects have been selected, the filter located at the top of the **Property Editor** (see Figure 14.7) can be used. Use the drop down box to select the specific object type required. Then only properties relevant to that type will be displayed in the **Property Editor**. These properties may then be changed collectively. Note however that this filter mode cannot be used to select specific object types for e.g. deletion or moving. For this it is necessary to use the **Selection Filter** described above.


Property Editor

All (24)

All (24)
External Boundaries (10)
Vertices (10)
Solids (2)
Internal Boundaries (2)

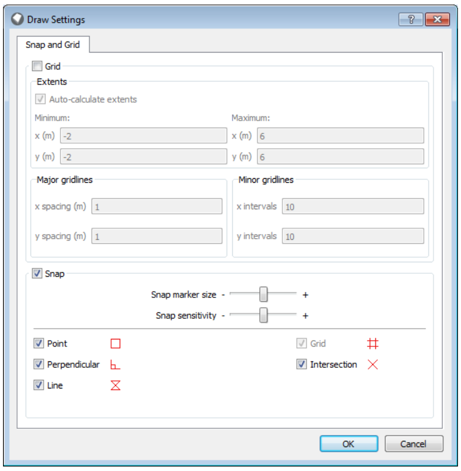
Figure 14.7: The Selection Filter dialog

14.4.3 Multiple Selection

Once a selection has been made using ‘Rectangle’ or ‘Click’, additional objects may be added to the selection by holding the **CTRL** key down while making additional selections using either ‘Rectangle’ or ‘Click’. Already selected objects may also be removed from the selection by re-selecting them using either ‘Rectangle’ or ‘Click’.

14.5 Snapping to Other Objects

It is possible to snap to most other geometrical objects on the screen. Extensive control is provided by the **Draw** >**Settings** menu as shown in Figure 14.8.



Draw Settings

Snap and Grid

☐ Grid

Extents

☑ Auto-calculate extents

Minimum: x (m) -2, y (m) -2

Maximum: x (m) 6, y (m) 6

Major gridlines: x spacing (m) 1, y spacing (m) 1

Minor gridlines: x intervals 10, y intervals 10

☑ Snap

Snap marker size - +

Snap sensitivity - +

☑ Point ☑ Grid

☑ Perpendicular ☑ Intersection

☑ Line

OK Cancel

Figure 14.8: The Draw Settings dialog in the Draw menu

Global control over snap is also provided by the SNAP button on the **Status bar**.

14.6 Modifying the Geometry

14.6.1 Using the Mouse

Any geometry object (**Solid**, **Boundary**, **Vertex**) may be selected and then dragged using the mouse (hold down the left button while moving the mouse). This provides a quick and flexible way to modify the geometry. If the modification should distort the geometry into an invalid form (e.g. turn a polygon inside out) then a warning message is displayed and the original geometry is restored.

The following actions are possible:

- Dragging a **Solid object** will drag the solid and its adjacent **Boundary** and **Vertex objects**.

- Dragging a **Boundary object** will drag the boundary and its end point **Vertex objects.**
- Dragging a **Vertex object** will drag the vertex and the ends of the adjacent **Boundary objects**.

Dragging is enabled by clicking on the DRAG button on the **Status bar**. Dragging may be constrained to orthogonal directions only by clicking the ORTHO button on the **Status bar** or by pressing **F8**.

To **Delete**, the following methods are recommended for the listed object types:

Vertex and Boundary drag the Vertex at one end point of the Boundary onto the Vertex at the other end point of the Boundary. The Vertex objects will be merged and the Boundary object deleted.

Vertex Select the Vertex and click Delete ☒. The Vertex and one of the adjacent Boundary objects will be deleted. It is not defined which of the two Boundary Objects will be deleted. If this would result in an ambiguous or illegal geometry this action is not permitted. To ensure a specific Boundary Object is deleted, use the method for deleting a Vertex and Boundary.

Boundary Select the Boundary and click Delete ☒. The outcome for this action depends on the location of the Boundary:

- If the Boundary object is an internal interface between two Solids, then the Boundary object is deleted and the Solids are merged.
- If the Boundary object is an external Boundary, it will be deleted together with its adjacent Vertex objects and one of the adjacent Boundary objects. The Vertex objects at the other end points of these deleted Boundary objects will be linked by the remaining Boundary. It is not defined which of the two Boundary Objects will be deleted. If this action would result in an ambiguous or illegal geometry this action is not permitted.

Solid Select the Solid and click Delete ☒. The Solid is then deleted together with all adjacent Boundary and Vertex objects that are not shared with other Solids.

It is usually preferable to delete objects by dragging and merging so that the properties of the remaining amended objects are retained.

14.6.2 Connecting Geometry Objects

To connect a **Solid object** to another **Solid object**, it is best to work with the relevant vertices. Ensuring that Snap to Point is activated (see Section 14.5) will make certain that the objects share common vertices rather than simply having vertices in very close proximity to each other.

For the example in Figure 14.9, two initially unconnected square solid zones are to be modified so that, after the process is completed, they share a common boundary:

a) The first vertex is selected. It is then clicked and the left mouse button held down.

b$_i$) The selected vertex is dragged over the target vertex (a red rectangle signifies that the two will be merged upon release the left mouse button). The left mouse button is then released.

b$_{ii}$ and c) The above steps are repeated for the second vertex.

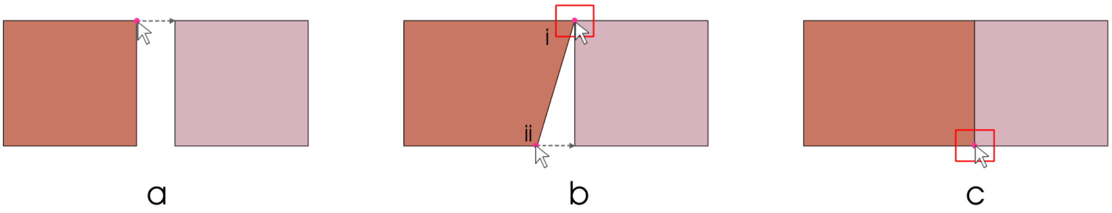


Figure 14.9: Connecting two solids by merging their vertices

14.6.3 Overlapping Geometry Objects

To overlap one **Solid object** with another, drag the former over the latter. This process will then split the original two **Solid objects** into three new **Solid objects**. If a **Solid object** is dragged over more than one other **Solid object** then a multiple split will be carried out.

For the example in Figure 14.10, two initially unconnected square solid zones are to be modified so that, after the process is completed, they overlap one another:

1. The first solid is selected. It is then clicked and the left mouse button held down.
2. The selected solid is dragged over the target solid and the left mouse button is then released.
3. A new zone is created by the overlapping areas of the two solids. Should the two original solids have different associated Slab Definitions and properties (as in this case), the new zone will contain the properties and structural objects of one of the original solids. It is undefined as to which solid the properties will be duplicated from.

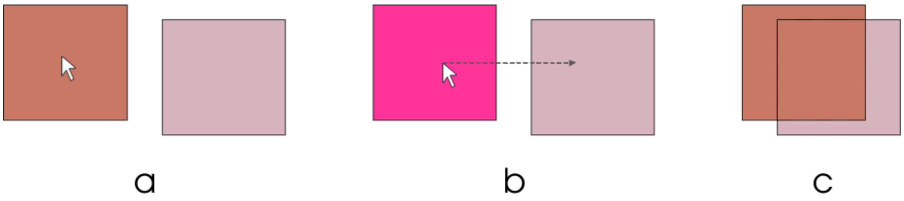


Figure 14.10: Overlapping two solids using drag and drop: a) selection of the first solid; b) dragging the solid and c) dropping the solid and creation of a new zone.

14.6.4 Changing the End Vertex of a Boundary

There are several ways in which the end vertex of a line can be changed. However, in situations where the geometry is perhaps rather complex, the following method may be used (Figure 14.11):

1. Using the **Line** function (see Section 14.5) draw a new boundary line in the desired position.
2. Use the mouse pointer to select the original boundary line then press the **Delete** button to remove it.
3. The properties and Slab Definitions in the **Solid** created in step 2 now will be duplicated from one of the original zones. It is undefined as to which solid the properties will be duplicated from.
4. If desired / appropriate, the original vertex may now be deleted.

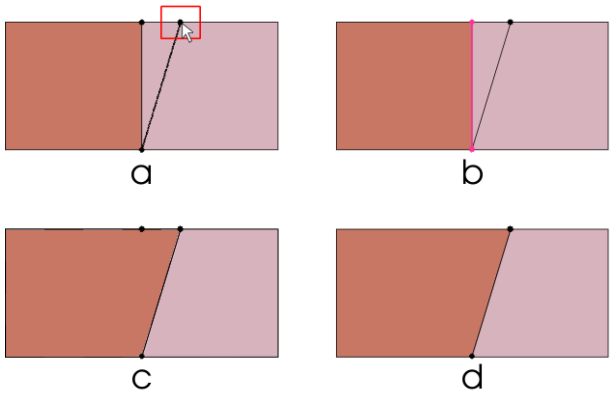


Figure 14.11: Moving a Boundary

Easier methods in the above case would have been to edit the coordinates of the vertex in the **Geometry Editor** or drag and drop the original endpoint of the line using the mouse (possibly with ORTHO enabled). However, these shortcut approaches are not always suitable in practice, for example where the vertex also defined the geometry of another **Solid** which was to be left unchanged.

14.6.5 Creating One Object Inside Another

It is often useful to create a zone that lies entirely within another solid (for example to model a drop panel or void). To achieve this, simply draw the new zone in the required position using the rectangle (▭) or polygon (⬠) draw functions. Additional boundary lines will be created in order to link the new zone to the rest of the model and the new zone will automatically be assigned the structural object properties of the surrounding solid.

To create a void, select the new zone with the mouse and press the Delete button (Figure 14.12).

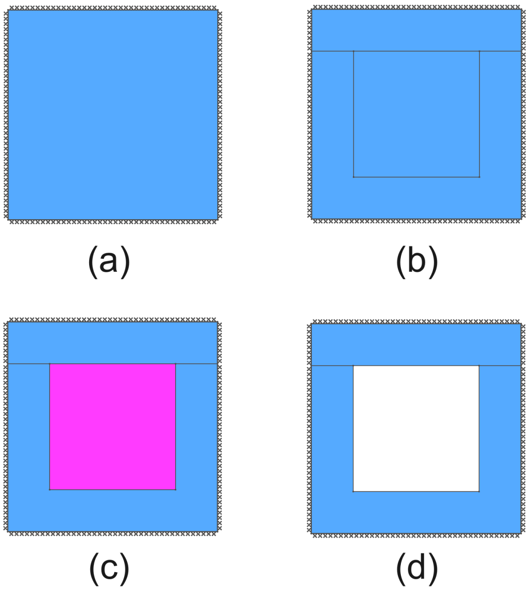


Figure 14.12: Creating Voids Within a Solid: (a) the solid; (b) creation of a new zone; (c) selection of the new zone and (d) deletion to create a void.

14.6.6 Using the Geometry Editor

Instead of utilizing the mouse, the coordinates of points making up any geometry object may be directly edited within the **Geometry Editor**.

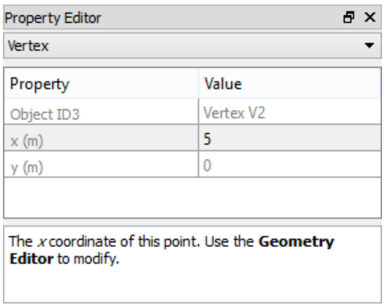
Select the required object and its coordinates will appear in the **Geometry Editor**. When all changes have been made, click the **Apply** button in the Editor to commit the changes.

14.7 Undo/Redo

Many specific modifications may be undone utilising the Undo button ↶ or the menu **Edit**, **Undo**. Any undone actions may be redone using the Redo button ↷ or the menu **Edit**, **Redo**. If **Undo** or **Redo** are not available then the toolbar buttons and menu items are disabled (appear in grey). Hovering the mouse over the Redo or Undo button will display a tooltip describing the last action.

14.8 Editing Geometry Object Properties

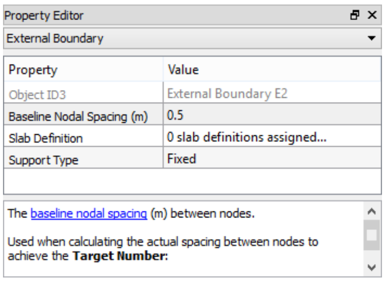
In addition to displaying the coordinates of a **Geometry Object** in the **Geometry Editor**, selecting any object displays its properties in the **Property Editor** and these may be edited. The properties available for a Vertex, Boundary and Solid are depicted in Figure 14.13, Figure 14.14 and Figure 14.15.



Property	Value
Object ID3	Vertex V2
x (m)	5
y (m)	0

The *x* coordinate of this point. Use the **Geometry Editor** to modify.

Figure 14.13: Property Editor display for a **Vertex**

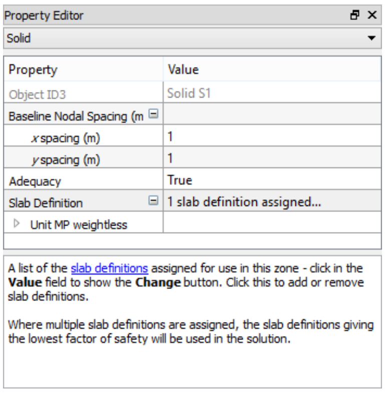


Property	Value
Object ID3	External Boundary E2
Baseline Nodal Spacing (m)	0.5
Slab Definition	0 slab definitions assigned...
Support Type	Fixed

The baseline nodal spacing (m) between nodes.

Used when calculating the actual spacing between nodes to achieve the **Target Number**.

Figure 14.14: Property Editor display for a **Boundary**



Property	Value
Object ID3	Solid S1
Baseline Nodal Spacing (m ⊟	
x spacing (m)	1
y spacing (m)	1
Adequacy	True
Slab Definition ⊟	1 slab definition assigned...
▷ Unit MP weightless	

A list of the slab definitions assigned for use in this zone - click in the **Value** field to show the **Change** button. Click this to add or remove slab definitions.

Where multiple slab definitions are assigned, the slab definitions giving the lowest factor of safety will be used in the solution.

Figure 14.15: Property Editor display for a **Solid**

Chapter 15

Defining and Assigning Structural Properties

15.1 Introduction

Before analysis can take place, and generally following definition of the problem geometry (see Chapter 14), structural properties must be assigned to each **solid object**.

Structural properties in LimitState:SLAB are contained within **Slab definitions**. These are effectively materials that can be applied to different areas of the model.

15.2 Slab Definitions

The properties that constitute a **Slab definition** are as follows:

Type Defines the type (and therefore behaviour) of the definition:

- **Rigid** - does not permit yield lines to pass through it at any magnitude of load. Use of this material type on solids where it is known that they will not deform should enhance the solver efficiency, since it reduces the number of nodes and yield-lines that need to be considered.
- **Flexural** - the ‘standard’ structural definition type.

Name / ID A unique identifier / name

Color The color as displayed on screen

Unit Weight The unit weight of the slab in any area where this definition is applied

Thickness The thickness of the slab in any area where this definition is applied

Mp (Flexural only) The plastic moment of resistance per unit length. To allow for the presence of skewed and orthotropic reinforcement, this is split into two directions named ***First*** and ***Second***. The following may then be defined for each:

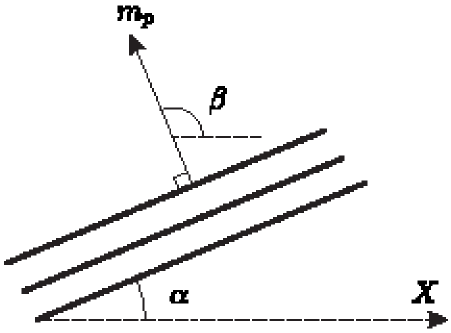


Figure 15.1: Direction of the moment capacity Mp

- ***Mp*$^+$**, The sagging plastic moment of resistance in the direction specified by the **Angle**.
- ***Mp*$^-$**, The hogging plastic moment of resistance in the direction specified by the **Angle**.
- ***Angle (°)***, The angle (anticlockwise) described between the global x axis and the direction in which M$_p$ is acting. Note that this is NOT the angle of the reinforcing bars (α in Figure 15.1), rather it is the angle NORMAL to them (β in Figure 15.1).

15.2.1 Predefined Slab Definitions

A number of predefined **Slab definitions** are available at all times. These are identified by a padlock in the corner of the icon. These are provided to allow an easy introduction to LimitState:SLAB and may be used as templates for user defined definitions. The properties are not intended to correspond to those in any specific standard (these could be defined by the user if required). It is *not* anticipated that these slab definitions will be used for any 'real' design or analysis calculations.

Note that the set of predefined slab definitions provided is determined by the chosen system of units to be used in the software. If the software has been set to work in Imperial units, then a separate set of predefined 'Imperial' slab definitions are provided. The reason for this is simply convenience in terms of providing structural properties with typical properties with rounded values. Thus 'Unit Mp Concrete [Imperial]' will not have quite the same properties as 'Unit Mp Concrete'.

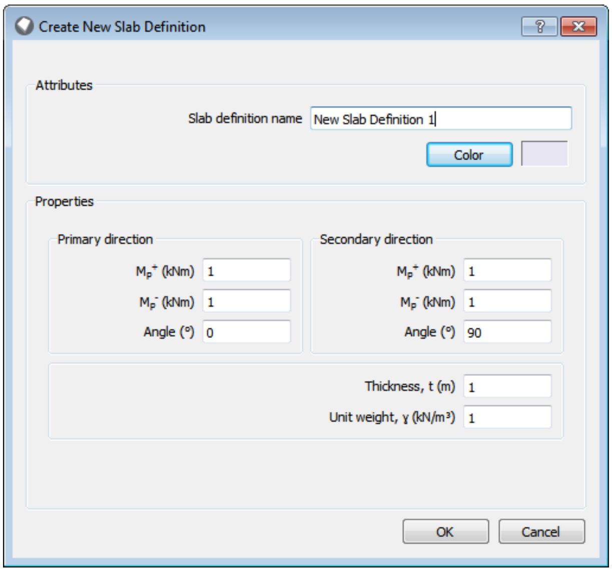
15.2.2 User Defined Slab Definitions

It is also possible to define bespoke anisotropic slab materials. Here, the user specifies appropriate, pre-determined plastic moments of resistance in two directions.

By default, LimitState:SLAB assumes that the reinforcement bars are placed perpendicular to each other along the Cartesian x and y axes, however this may be overridden.

15.2.3 Creating a New Slab Definition

Select 'New slab definition...' in the context menu (or from the main menu, select Tools - Create New Slab Definition...) to display the **Create New Slab Definition** dialog as shown in Figure 15.2.



Slab definition name: New Slab Definition 1

Primary direction: M_p^+ (kNm) 1; M_p^- (kNm) 1; Angle (°) 0

Secondary direction: M_p^+ (kNm) 1; M_p^- (kNm) 1; Angle (°) 90

Thickness, t (m) 1

Unit weight, γ (kN/m³) 1

Figure 15.2: Create New Slab Definition Dialog

Enter the required parameters and click **OK**.

15.2.4 Creating a Duplicate Slab Definition

Select ***Duplicate Slab Definition*** in the context menu. A new material will be created with the name *Copy of X* where 'X' was the parent **Slab Definition**.

15.2.5 Deleting a Slab Definition

To delete a slab definition, select ***Delete Slab Definition*** in the context menu. This will delete the selected item.

15.3 Exporting and Importing Slab Definitions

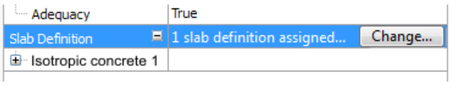
To export or import the properties listed in the **Slab Definition Explorer** to a .csv (comma separated values) file, select ***Export Slab Definitions...*** or ***Import Slab Definitions...*** in the context menu. The file format allows the data to be easily edited within a text editor or spreadsheet if required.

15.4 Assigning a Slab Definition

Slab definitions may be assigned to a **Solid**, **Boundary** or **Vertex object** by the following methods:

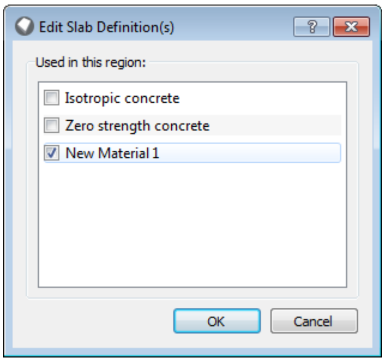
Drag and drop Select a slab definition in the Slab Property Explorer and drag it onto the required Geometry Object

Change dialog Select the required Geometry Object. In the **Property Editor** click on the right hand box in the row ***Slab definitions(s)*** to display the *Change* button (see Figure 15.3). Click this to display the **Edit Object Structural Properties** dialog (see Figure 15.4). Check or uncheck the relevant boxes to include or remove slab definitions from the object.



Adequacy	True
Slab Definition	1 slab definition assigned...
⊞ Isotropic concrete 1	

Figure 15.3: Displaying the ‘Change’ button in the Property Editor



Edit Slab Definition(s)

Used in this region:

□ Isotropic concrete
□ Zero strength concrete
☑ New Material 1

Figure 15.4: Edit Structural Object(s) dialog box

If a slab definition is assigned to an object that already has one or more definitions assigned to it, a warning message appears asking if the new property is to replace the existing one.

Chapter 16

Setting Boundary Conditions

The current boundary conditions for the problem are displayed graphically (Figure 16). They may also be viewed in the **Property Editor** by selecting any boundary. In the **Property Editor** it is also possible to set the boundary type.

16.1 External Boundaries

External boundaries in LimitState:SLAB can take one of the following forms:

Free The boundary is free to displace and / or rotate in any direction.

Simple The boundary is fixed against displacements in all directions. Rotations of the slab around the axis of the boundary are permitted without yield-line formation.

Fixed The boundary is fixed against displacements in all directions. Rotations of the slab around the axis of the boundary are only permitted as a result of yield-line formation.

Partially Fixed The boundary is fixed against displacements in all directions. Rotations of the slab around the axis of the boundary are only permitted as a result of yield-line formation at a moment equal to the specified ***Support Strength Ratio*** multiplied by the strength of the adjacent slab.

Symmetry The boundary represents a line of symmetry in the model.

16.2 Internal Boundaries

Internal boundaries in LimitState:SLAB can take one of the following forms:

Free The boundary is free to displace and / or rotate in any direction.

Knife-edge The boundary is fixed against displacements in all directions. with moments over the support and rotation around the line of the axis being permitted. A yield-line will form if the hogging moment over the support reaches or surpasses the limiting moment resistance of the slab.

16.3 Lift-off

In certain circumstances it may be desirable to allow a slab to be supported from vertical downwards displacement, but for it to be able to move vertically upwards. By setting the ***Support Lift-Off*** field to *true*, LimitState:SLAB will permit this to occur.

Note that lift-off can only be specified for the following boundary types:

- **Simple** (external boundary)
- **Knife-edge** (internal boundary)

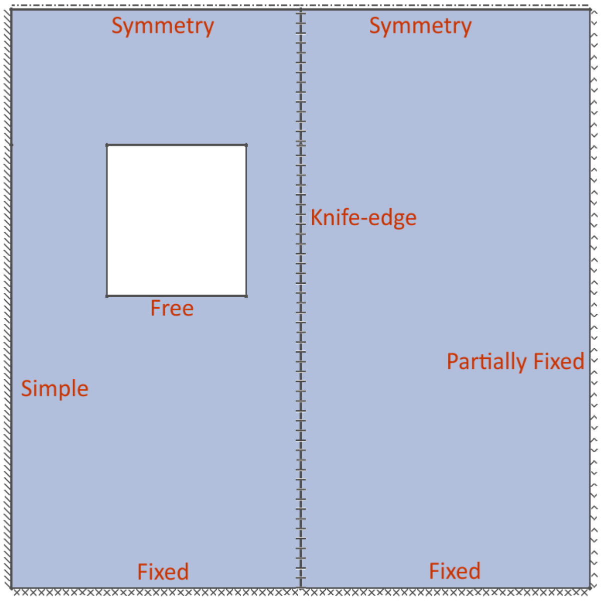


Figure 16.1: Boundary conditions in LimitState:SLAB

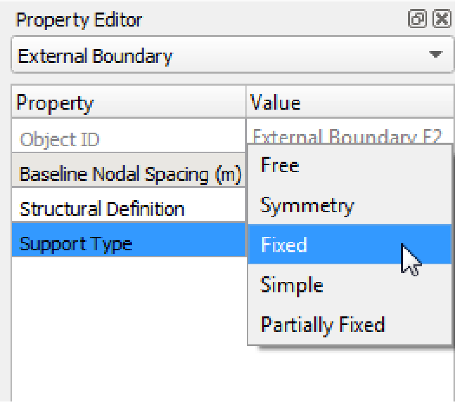
16.4 Modifying boundary conditions

16.4.1 General

To change a boundary condition:

- Select one or more boundaries.
- In the **Property Editor**, select the appropriate boundary type (***External boundaries*** or ***Internal boundaries***) in the top drop-down.

- Click the field next to the ***Support Type***. A drop-down menu will be shown (Figure 16.2).
- Select the type of support (boundary condition) that you wish to apply to the boundaries.
- Click away from the drop-down to apply the chosen boundary condition.



Property	Value
Object ID	External Boundary F2
Baseline Nodal Spacing (m)	
Structural Definition	
Support Type	

Figure 16.2: Boundary conditions in the **Property Editor**

16.4.2 Lift-off

Support lift-off occurs when a ***Knife-edge*** or ***Simple*** support is permitted to move in the upwards (vertical) direction while still being supported against downwards movement.

To allow a boundary to undergo lift-off:

- Select one or more ***Knife-edge*** or ***Simple*** supports
- In the **Property Editor**, Set ***Support lift-off*** to *True*

Chapter 17

Applying Loading

Loading in LimitState:SLAB is managed in the following way:

1. **Loads** are defined in terms of their type and magnitude - either on screen (using the shortcut icons) or in the **Loads Database**.
2. **Partial Factor** sets are defined within the **Load Case Manager**.
3. **Load Cases** are then generated using combinations of the **Loads** and **Partial Factors**.

Four types of load can be set:

1. Self-weight loads
2. Pressure loads
3. Line loads
4. Point loads

In line with Eurocode 1, loads are specified as being either **Permanent**, **Variable**, and **Accidental**. The purpose of these labels is purely to permit correct application of Partial Factors (see **Load Case Manager**, Chapter 17.3). No additional meaning is given to these labels. Each load is assumed to act only along the z axis (negative downwards).

17.1 Adequacy Factors

In order that the solver can find a solution that causes collapse, it is necessary to apply an **Adequacy factor** to one or more of the loads or self weights. An adequacy factor $>$ 1.0 means that the slab is safe against collapse (within the scope of the analysis technique), an adequacy factor $<$ 1.0 means that the slab is unsafe. This is discussed further in Section 6.2.

17.2 Defining a Load

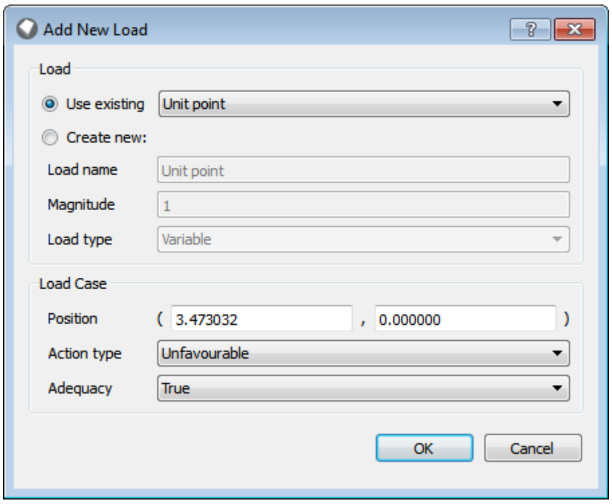
17.2.1 Defining a Point Load

17.2.1.1 On Screen

Defining a point load on screen will simultaneously add the load ‘definition’ to the **Loads Database** and in to an active **Load Case**.

To define a point load on screen:

- Click the **Point Load** icon
- Using the crosshair cursor (+), select a location on the slab to load.
- The **Add New Load** dialog will appear (see Figure 17.1). Here you can change the magnitude and fine-tune the location of the load.
- If you wish to use an *existing* load definition, ensure the ***Use existing*** radio button is selected and choose the appropriate load from the drop-down menu.
- If you wish to create a *new* load definition, ensure the ***Create new*** radio button is selected. It is then possible to specify:
  - *Load name*
  - *Magnitude* (can be positive or negative)
  - *Load type* (affects the partial factors that are applied to this load)
- In the ***Load Case*** section, it is possible to specify:
  - *Position* (x and y)
  - *Action type* (can be Neutral, Favourable or Unfavourable - see Section 6.2.4)
  - *Adequacy* (determines whether this load is scaled during the search for a solution - (see Section 6.2). Set to ‘True’ by default)
- Once you are happy with the settings, click the ***OK*** button. The point load will appear as a purple circle containing a cross when viewed from above, or as a purple arrow when viewed in 3D.
- Point loads generated in this way will automatically be added to **Load Case 1** if there is only a single load case. Where a problem contains more than one load case, the new point load will be added to the active case (which is displayed in the **Load Case Scroll Box** and also denoted by the active tab at the bottom of the **Viewer Pane**).



Add New Load

Load

● Use existing: Unit point

○ Create new:

Load name: Unit point

Magnitude: 1

Load type: Variable

Load Case

Position (3.473032 , 0.000000)

Action type: Unfavourable

Adequacy: True

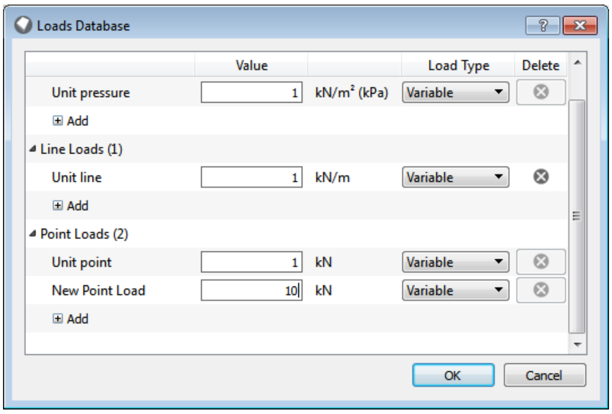
Figure 17.1: The **Add New Load** dialog for Point loading

17.2.1.2 Using the Load Database

Defining a Point Load in the **Load Database** will allow it to be used in the project, but will not add it to a **Load Case**. This must be done separately.

To define a point load using the load database:

- Open the **Load Case Manager**. This can be done by:
  - Clicking on the **Load Case Manager** icon, or
  - Going to the **Loads** menu and selecting **Load Case Manager**
- Click on the **Loads Database** button.
- In the **Loads Database** (see Figure 17.2), scroll to the *Point Loads* section and select the *Add* option (+).
- Enter the details for the new load by highlighting the relevant field and entering the necessary data:
  - *Load name*
  - *Value* (i.e. Magnitude - can be positive or negative)
  - *Load type* (affects the partial factors that are applied to this load)
- It is also possible to delete the load (provided it is not used in an active **Load Case** by clicking the ***Delete button***.
- Once you are happy with the settings, click the ***OK*** button. The point load will now be available for selection when defining a new Point Load within a **Load Case**.



Loads Database

	Value		Load Type	Delete
Unit pressure	1	kN/m² (kPa)	Variable	⊗
⊞ Add				
◢ Line Loads (1)				
Unit line	1	kN/m	Variable	⊗
⊞ Add				
◢ Point Loads (2)				
Unit point	1	kN	Variable	⊗
New Point Load	10	kN	Variable	⊗
⊞ Add				

Figure 17.2: Adding a new point load in the **Loads Database**

17.2.2 Defining a Line Load

Line loads are displayed in green on screen.

17.2.2.1 On Screen

As with the point load, defining a line load on screen will simultaneously add the load 'definition' to the **Loads Database** and in to an active **Load Case**.

To define a line load on screen, click the **Add Line Load** icon, , then follow the same general process as for a point load (Section 17.2.1.1). The ***Magnitude*** is defined as force per unit length.

17.2.2.2 Using the Load Database

Defining a Line Load in the **Load Database** will allow it to be used in the project, but will not add it to a **Load Case.** This must be done separately.

To define a line load using the load database, follow the same general process as for a point load (Section 17.2.1.2). The ***Value*** is defined as force per unit length.

17.2.3 Defining a Pressure Load

17.2.3.1 On Screen

Defining a pressure load on screen will simultaneously add the load 'definition' to the **Loads Database** and in to an active **Load Case**.

To define a pressure load on screen:

- Click the **Pressure Load** icon

- Using the mouse cursor, select the solid zones on the slab to load (see Figure 17.3). To select multiple zones, hold down the CTRL button on the keyboard while clicking. Selected solids will turn pink and their ID will be displayed in the dialog. To select all the solids in the model, click the ***Select All*** button.

- Click ***OK***.

- The **Add New Load** dialog will appear (see Figure 17.4). Here you can change the magnitude and fine-tune the positioning of the load.

- If you wish to use an *exising* load definition, ensure the ***Use existing*** radio button is selected and choose the appropriate load from the drop-down menu.

- If you wish to create a *new* load definition, ensure the ***Create new*** radio button is selected. It is then possible to specify:

  - *Load name*
  - *Magnitude* (can be positive or negative)
  - *Load type* (affects the partial factors that are applied to this load)

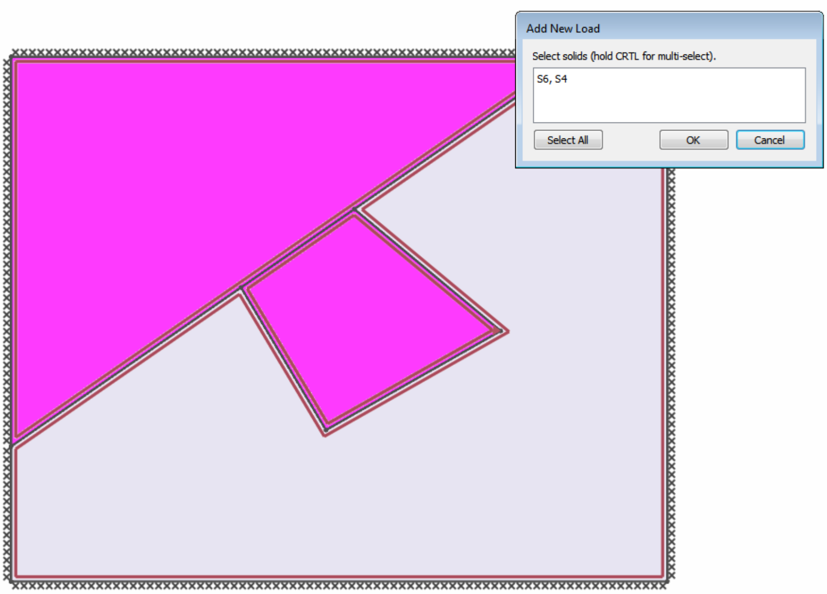
- In the ***Load Case*** section, it is possible to specify:

  - *Position* (the ID of each loaded solid, click *Change* to alter these)
  - *Action type* (can be Neutral, Favourable or Unfavourable - (Section 17.2.1.2))
  - *Adequacy* (determines whether this load is scaled during the search for a solution - see Section 6.2. Set to 'True' by default)

- Once you are happy with the settings, click the ***OK*** button. The pressure load will appear as a deep red line around the edge of each loaded solid. A triangle near the top-right corner of each solid is selectable and allows the user to query the properties of the load in the **Property Editor**.

  When viewed in 3D, a pressure load is represented as a series of joined 2D arrows around the edge of the loaded solid.

- Point loads generated in this way will automatically be added to the active case (which is displayed in the **Load Case Scroll Box** and also denoted by the active tab at the bottom of the **Viewer Pane**).

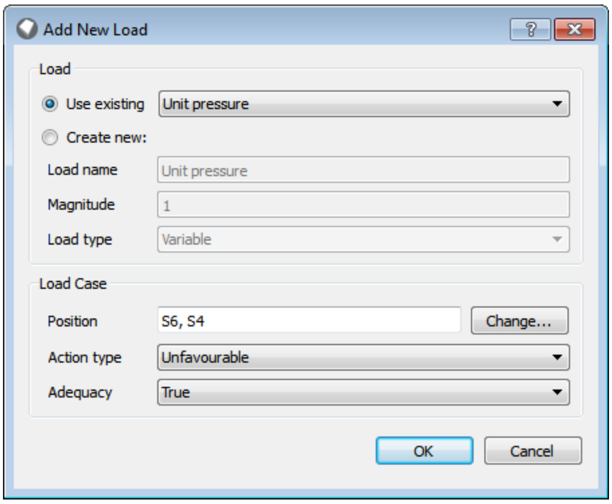


Add New Load

Select solids (hold CRTL for multi-select).

S6, S4

Figure 17.3: Adding a pressure load to multiple solids on screen



Add New Load

Load

● Use existing: Unit pressure

○ Create new:

Load name: Unit pressure

Magnitude: 1

Load type: Variable

Load Case

Position: S6, S4

Action type: Unfavourable

Adequacy: True

Figure 17.4: Adding a new Pressure Load in the **Loads Database**

17.2.4 Defining Self-Weight Loads

Self-weight loading is calculated individually for each solid based upon the *Slab Definition* that has been applied to it. By default it is not applied to any solids in the problem. However, it can be set via the **Load Case Manager** (see Section 17.3).

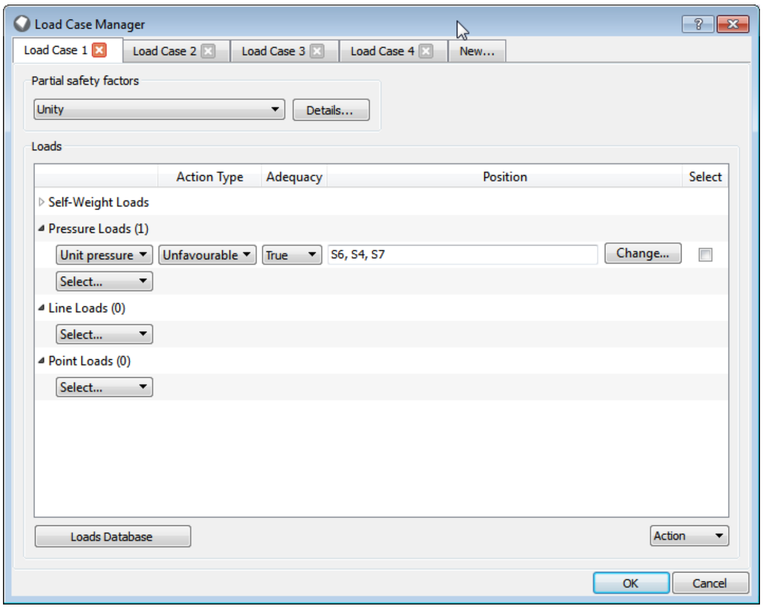
17.3 The Load Case Manager

The **Load Case Manager** (depicted in Figure 17.5) is a powerful facility that permits several different combinations of loads and partial factors to be solved in a single analysis. This is useful where several design combinations of partial factors may need to be checked for the same geometry. It is also used to specify partial factors for solution of single problems.

There must be at least one active **Load Case** in the problem in order for the software to carry out an analysis. A **Load Case** is generated by assigning a **Partial Factor** set to a defined set of loads (a **Load Case**).

Load Cases are identified by a series of tabs at the top of the **Load Case Manager**. Each **Load Case** will, by definition, contain different loads and / or partial factor sets.

The **Load Case Manager)** (Figure 17.5) takes existing loads from the **Loads Database** and combines them with **Partial Factor** sets in one or more distinct 'Cases'.



Partial safety factors: Unity

Unit pressure | Unfavourable | True | S6, S4, S7 | □

Figure 17.5: The **Load Case Manager**

17.3.1 Partial Factors

17.3.1.1 Definition

By default, the partial factor set chosen for all LimitState:SLAB analyses is ***Unity***. That is, the **Adequacy factor** determined on solve is a straight multiplier on any applied load to which ***Adequacy = true*** has been set.

New partial factor sets are defined from within the **Load Case Manager** (see Figure 17.6). To create one:

- Open the **Load Case Manager** and select **New...** The **Partial Safety Factors** dialog will then be shown (Figure 17.7). Alternatively, to modify a Partial Factor Set that already exists, select it from the drop-down list then click the ***Details...*** button.

- If you wish to vary the partial factors according to the **Action Type** (see Section 6.3) then ensure that the *Vary unfavourable/favourable actions* checkbox is selected. This will expand the number of Partial Factor fields available.

- In the ***Loads*** section, enter appropriate MULTIPLIERS on the applied loading.

- In the ***Materials*** section, enter appropriate MULTIPLIERS on the properties defining the slab strength (i.e. moment resistances Mp^+ and Mp^-). For example, if the slab definitions are anticipated to be twice as weak as their moment resistances suggests, enter '0.5'.

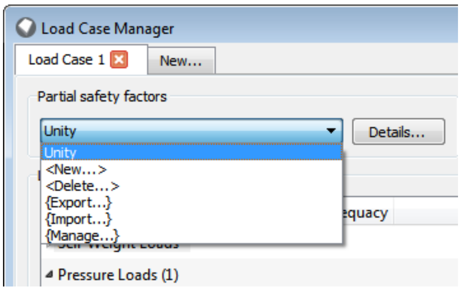
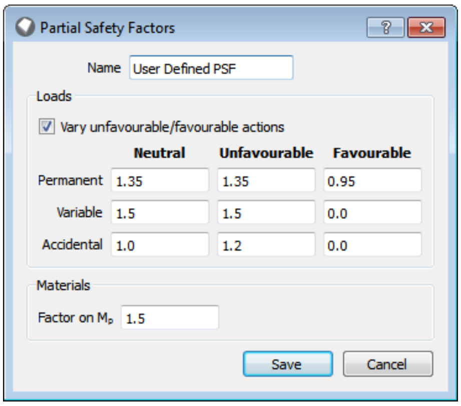


Figure 17.6: Partial Factors section in the **Load Case Manager**



Name: User Defined PSF

Loads

☑ Vary unfavourable/favourable actions

	Neutral	Unfavourable	Favourable
Permanent	1.35	1.35	0.95
Variable	1.5	1.5	0.0
Accidental	1.0	1.2	0.0

Materials

Factor on M_p: 1.5

Figure 17.7: New Partial Factors in the Load Case Manager

17.3.1.2 Deletion

To delete a **Partial Factor** set, simply select **Delete...** from the drop-down list. A warning will appear if the set will be removed from a Load Case that it is used in. If you choose to accept this, the 'Unity' set will be used in its place. Only user-defined **Partial Factor** sets may be deleted.

17.3.1.3 Exporting and Importing Partial Factor Sets

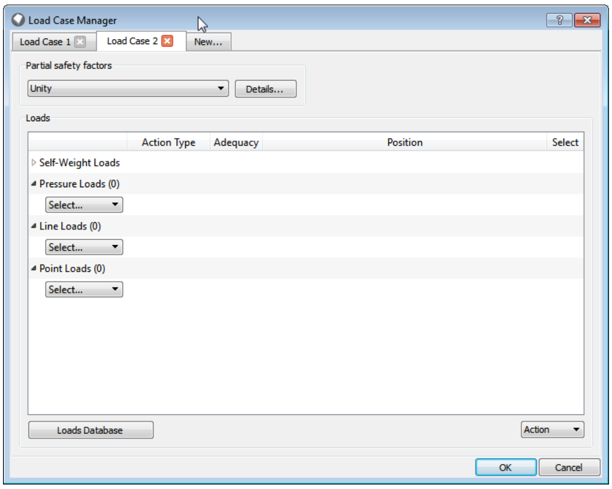
All partial factor sets listed in the drop down box may be exported to a .csv file by selecting **Export...**

Similarly, to import previously exported sets of partial factors from a .csv, select **Import...** (sets with the same name are not overwritten)

Note that all partial factors are saved with the main .slab file.

17.3.2 Defining a New Load Case

To create a single new Load Case, click on the **New..** tab at the top of the **Load Case Manager** dialog. A blank Load Case will then be created and displayed, as shown in Figure 17.8:



Partial safety factors: Unity

Figure 17.8: The LimitState:SLAB New Load Case dialog

To add partial factors to the Load Case:

- Select the appropriate partial factor set from the ***Partial safety factors*** drop-down list. Alternatively, define a new partial factor set (see Section 17.3.1).

To add loads to the Load Case:

- Select a load from the appropriate drop-down list on the left-hand side (*Pressure Load*, *Point Load* etc.). If the required load is not yet present, the **Loads Database** can be opened by selecting *Add New...* in the appropriate drop-down or by clicking on the ***Loads Database*** button (see Section 17.2).
- Decide on an ***Action Type*** (see Section 6.3.2).
- Decide whether the load is to be varied when determining the **Adequacy factor** (see Section 6.2).

- Select where the load is to be applied by clicking the ***Change...*** button and either selecting the appropriate solids (for a pressure load) or by drawing on screen (point or line loads).
- Repeat as necessary.

17.3.3 Copying Load Cases

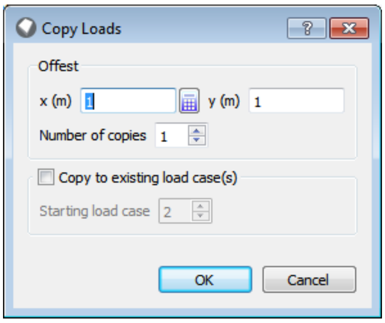
Aside from an empty load case, the **Load Case Manager** dialog provides the option to copy some or all of the data from an existing 'target' load case to one or more new cases. This provides the capability to 'move' a load across a slab.

To do this:

- Navigate to a load case containing the load(s) that you wish to copy.
- ***Select*** the load(s) to copy by checking the appropriate boxes in the column at the right of the table.
- In the ***Action*** drop-down list at the base of the table, select ***Copy***. The **Copy Loads** dialog will be shown Figure 17.9.
- Input the number of copies of the Load Case that are required and the distance to move the load(s) between each one.
- By default, the software will begin adding new Load Cases after the last in the existing list. However, by selecting ***Copy to existing load case(s)*** and entering a starting Load Case number, new cases can be superimposed over existing ones (i.e. copied loads will be added to any load that already existed).
- Click ***OK*** twice to exit the dialog.

Note: pressure loads may be transferred to new load cases. However, they will not be offset due to being assigned to specific solids.

Note 2: The software will automatically display the first Load Case when exiting the dialog. Loads that exist in other Load Cases will not be shown until the appropriate tab is selected.



Offest

x (m) 1 y (m) 1

Number of copies 1

□ Copy to existing load case(s)

Starting load case 2

Figure 17.9: The LimitState:SLAB Copy Load Case dialog

17.3.4 Deleting Loads from a Load Case

To delete loads from a Load Case:

- Navigate to a load case containing the load(s) that you wish to delete.
- ***Select*** the load(s) to copy by checking the appropriate boxes in the column at the right of the table.
- In the ***Action*** drop-down list at the base of the table, select ***Delete***. The loads will be removed from the current case.

Chapter 18

Analysis

18.1 Overview

To perform an analysis, on the **Analysis** menu click **Solve**. Alternatively this command can be accessed via the ▶ button on the toolbar; the keyboard shortcut for the command is **F5**.

The analysis procedure first allocates nodes to all zones and generates a list of potential yield-lines.

An initial analysis is then undertaken and the solver iterates towards the optimal solution by progressively adding yield-lines at critical positions (see Chapter II). Stages in the solution are displayed on the **Status bar**.

By default, the output displayed in the **Output** pane from an analysis is restricted to the critical load case and failure adequacy factor only. To enable the display of *all* iteration data, go to the **Preferences** dialog in the Tools menu, select the **Solve** tab and check the option to **Display detailed information in output window**.

18.2 The Solver

A solver is required to find the critical collapse load factor and associated collapse mechanism. The internal forces in the structure must satisfy all specified yield constraints; these are set up for a particular problem by LimitState:SLAB.

The solver used by LimitState:SLAB is Mosek, a powerful interior point linear programming solver. In LimitState:SLAB, Mosek is called as a subroutine and, to maximize efficiency, the problem data is passed *via* memory.

Prior to solving, LimitState:SLAB runs a number of pre-solve checks. These are:

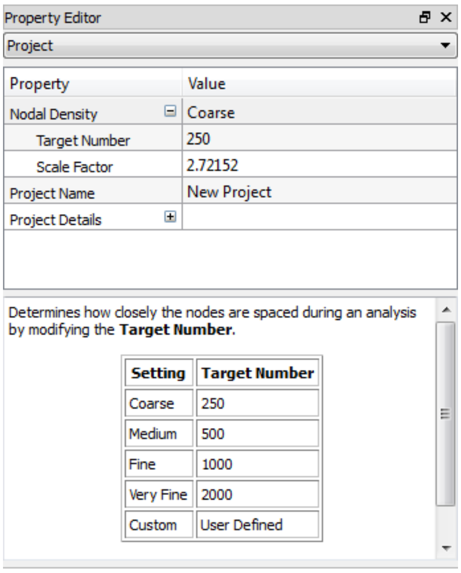
Check	Warning
Check if a license was held then lost	The connection to the network license server or hardware dongle was lost. You need to restart the application to be able to solve again.
Check if license does not have permission to solve for certain features	Cannot solve as the following feature(s) in this project are not supported by this <LICENSE_TYPE> license:
Check if project cannot be solved for one of the following reasons: 1) No slab definitions applied, 2) No support applied, or 3) No adequacy factor applied	The project cannot be solved yet because: 1) no materials have been applied, drag and drop a material onto a geometry object. 2) no support has been applied. or 3) no adequacy factor has been applied (to a load or solid object).

Table 18.1: Pre-solve checks carried out by LimitState:SLAB and their associated warnings.

18.3 Analysis Settings

18.3.1 Overview

The project **Property Editor** parameters (as shown in Figure 18.1) provide key control over the type and accuracy of the solution to be obtained.



Property	Value
Nodal Density ⊟	Coarse
Target Number	250
Scale Factor	2.72152
Project Name	New Project
Project Details ⊞	

Determines how closely the nodes are spaced during an analysis by modifying the **Target Number**.

Setting	Target Number
Coarse	250
Medium	500
Fine	1000
Very Fine	2000
Custom	User Defined

Figure 18.1: Project properties

Nodal Density The nodal density controls the resolution and accuracy of the solution obtained (Section 18.3.2).

18.3.2 Setting and Previewing the Nodes

Solution accuracy is determined by the number of nodes utilised in the solution as described in Section II. The number of nodes to be used may be set using the **Nodal Density** setting in the Project level parameters (accessible via the Property Editor). The settings are **Coarse** (250 nodes), **Medium** (500 nodes), **Fine** (1000 nodes) and **Very Fine** (2000 nodes). It is recommended that initial scoping calculations are carried out in Coarse mode, which typically generates solutions within a few seconds. For determination of the solution for final accuracy, the setting should be changed to **Fine** or higher using the **Custom** setting described below.

At any time, it is possible to view the arrangement of nodes prior to solve to check that these are as required. To do this click on the Preview Nodes button. This function may also be accessed via the **Preview Nodes** menu item on the **Analysis** menu. It is necessary to click **Unlock** afterwards to edit the problem parameters.

For advanced use, the **Nodal Density** may be set to **Custom**. The user has two options on how to control the Nodal density:

Target Number Set this to the total number of nodes that the software will attempt to use when solving the problem. The software will normally be able to meet this target within a few percent. Altering this value will cause the Scale Factor on the Baseline Nodal Spacing to change, thus altering the Actual Nodal Spacing:

Actual Nodal Spacing = Baseline Nodal Spacing / Scale Factor

Note: The Actual Nodal Spacing is calculated by the software to determine the spacing required to achieve the Target Number of nodes and cannot be directly modified by the user. Modifying the Target Number will automatically cause the Scale Factor to change.

Scale Factor A global factor used to scale the Baseline Nodal Spacing to achieve (or alter) the Target Number of nodes.

Actual Nodal Spacing = Baseline Nodal Spacing / Scale Factor

i.e. doubling the Scale Factor causes the number of nodes used along boundaries to double and the number of nodes used in solids to quadruple.

Note: Modifying the Scale Factor will automatically cause the Target Number to change.

Setting the Baseline Nodal Spacing is described in Section 18.3.3.

18.3.3 Setting Nodal Distribution within Solids

The baseline nodal spacing within **Geometry objects** may be set by selecting the required object and modifying the following parameter(s) in the **Property Editor**:

Boundary object Nodal spacing: this is the baseline spacing along the Boundary object.

Solid object Linear nodal spacing: Click the ⊞ to view the x-spacing and y-spacing. These specify the baseline spacing on a rectangular grid within the solid object. The software will position the grid within the solid appropriately.

If it is expected that failure will not occur in certain geometry objects then setting a large nodal spacing in these objects will ensure computational resources are not wasted.

18.4 Pre-Solve Diagnostics

During model generation and prior to solving, LimitState:SLAB runs a number of checks to ensure the integrity and rationality of the model.

Some checks are carried out continuously and result in singular warning or error messages being displayed to the user. These pertain to issues such as invalid licenses and geometries and are provided in Table 18.2.

Check	**Warning**
Check if a license was held then lost	The connection to the network license server or hardware dongle was lost. You need to restart the application to be able to solve again.
Check if license does not have permission to solve for certain features	Cannot solve as the following feature(s) in this project are not supported by this <LICENSE_TYPE> license:’
Check for two coincident vertices	Two coincident points encountered
Check for a zero length line	Zero length boundary encountered
Check for two coincident boundaries	Two coincident boundaries encountered
Check for two intersecting lines without a vertex at the crossover point	Vertex missing at boundary object intersection.
Check for an ‘invalid’ polygon	Illegal solid geometry.
Check for a zero area polygon	Zero area solid.
Check for a problem where the overall area is too small	Total area of problem is too small, which may lead to numerical tolerance problems - for more details, see here.
Check for solids overlapping without vertices on their coincident points	Solids are overlapping (see output window for details.)

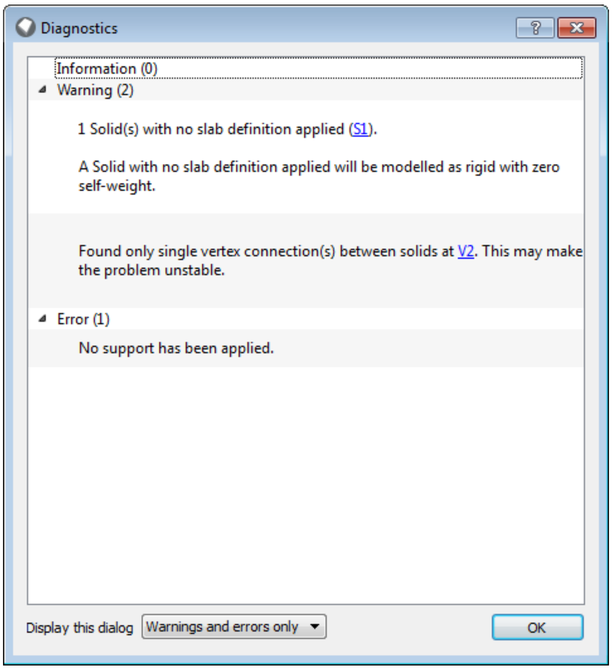
Table 18.2: Continuous checks carried out by LimitState:SLAB and their associated warnings.

Other messages are collated and shown at solve-time, or when the user opens the **Diagnostics tool** dialog (as shown in Figure 18.2) by going to the **Analysis** menu and selecting **Diagnostics...** These messages are categorized according to severity as follows:

Information Useful reminders about the problem set-up that require no user action prior to solve.

Warning Messages regarding the problem set-up that *may* require user action prior to solve, but which do not prevent solving.

Error Messages regarding the problem set-up that *must* be resolved by the user prior to solve.



1 Solid(s) with no slab definition applied (S1).

A Solid with no slab definition applied will be modelled as rigid with zero self-weight.

Found only single vertex connection(s) between solids at V2. This may make the problem unstable.

No support has been applied.

Display this dialog: Warnings and errors only

Figure 18.2: The LimitState:SLAB Diagnostics Tool

The **Display this dialog** drop-down menu at the base of the **Diagnostics** tool allows the user to specify the circumstances under which the dialog is displayed:

Always Displays the dialog before every **Solve**, irrespective of whether there are any warnings or errors to report.

Warnings & Errors only Displays the dialog before **Solve** only when there are warnings or errors to report.

Errors only Displays the dialog before **Solve** only when there are errors to report.

If the setting is changed to *Errors only* then any warnings encountered will instead be highlighted in the **Output Pane** by a hyperlink. Clicking the hyperlink will open the **Diagnostics** dialog with the warnings present.

A list of the messages provided by the **Diagnostics** tool and their interpretation is provided in Table 18.3.

Severity	Check	Warning
Information	Check if self-weight loading is specified, but all structural definitions are 'Unit MP Weightless'.	Problem uses 'Unit MP Weightless' definition throughout, however self-weight loading is also specified. In order to have any effect, one or more solids will require a definition with non-zero self-weight properties.
Warning	Check that the problem size is sufficient to avoid numerical tolerance issues.	Defective geometry encountered - the total area of problem is small, which may lead to numerical tolerance issues.

Continued on next page...

Warning	Check for a single **Vertex** joining two or more **Solids**.	Found only single vertex connection(s) between solids at VERTEX. This may make the problem unstable.
Warning	Check for **Solids** without any set material type.	#NUM Solid(s) with no material applied (LIST). A Solid with no material applied will be modelled as rigid with zero self-weight.
Warning	Check that Boundaries do not have significantly higher nodal spacing than the solids to either side	One or more zone boundaries have significantly higher nodal spacings than their adjacent solids: LIST. This can lead to poor results.
Warning	Check for self-weight load cases applied to solid zones without self-weight properties	[<SOLID> <LOAD_CASE>] - Self-weight loading, NO self-weight properties.
Warning	Check for self-weight properties applied to solid zones without self-weight loading	[<SOLID> <LOAD_CASE>] - NO self-weight loading, self-weight properties.
Error	Check that the problem size is greater than 0.25x10^{-4} m^2.	Defective geometry encountered - the total area of problem is too small.
Error	Check that at least one **Solid** has an applied **Material**.	No materials have been applied, drag and drop a material onto a geometry object.
Error	Check that at least one **Boundary** is acting as a **Support**.	No support has been applied.
Error	Check that a geometry has been defined.	No geometry objects have been defined.
Error	Check that **Adequacy** has been defined as *True* for at least one load or weight.	An adequacy factor needs to be applied to either a load or to a solid object with non-zero self weight.

Table 18.3: Checks carried out by the LimitState:SLAB Diagnostics Tool.

18.5 Analysis Results

18.5.1 Collapse Load Factor Found

Following an analysis, the critical collapse load factor or ‘adequacy factor’, will be displayed in the **Output** pane. This is the factor that when applied to all ‘live’ loads (i.e. loads that have had **Adequacy** applied to them) causes collapse. This load factor may also be called a margin of safety.

When assessing a design using a design code analysis with partial factors applied to loads, a value of this factor of greater than or equal to 1.0 indicates that the design is safe. A value less than 1.0 indicates that it is unsafe.

In rare cases where a solution can’t be obtained for a load case, the output will contain a message in red text to alert the user to this fact. A link is provided to give more infomation on the underlying reasons for this.

18.5.2 No Solution Found

‘Locked’ result

It is possible that the applied load can be increased without limit. In this case the problem can be described as being geometrically ‘locked’.

‘Unstable’ result

It is possible that no solution can be found because the problem is ‘unstable’ under its own self weight and/or other applied forces. In this case, the calculation will fail because no viable equilibrium state can be identified. This result will typically occur if a body is loaded, but has no viable means of resisting the load. For example, the ‘unstable’ result will occur in a slab problem involving a single, simply supported edge. The slab here is free to rotate around the supported edge, providing no effective resistance to loading (either self-weight or applied).

‘Terminated’ result

If the user aborts the analysis (see below for details on how to do this) then a ‘terminated’ status message will be reported. Note also that the software will internally abort an analysis if the number of iterations required is excessive (though this should very rarely happen).

‘Unknown’ result

The solver used by the software is very robust but can occasionally encounter numerical difficulties, leading to failure to find a solution of definite status (i.e. it will fail to find a value for the ‘adequacy factor’ or the ‘locked’, ‘unstable’ or ‘terminated’ results). If this occurs then an ‘unknown’ status will be reported.

In such cases, it is often beneficial to try to solve the problem again, initially in completely unchanged form, and subsequently after very minor changes have been made to one or more of the following:

- nodal density
- material properties
- loading regime

However, in the rare instance that a solution is still not found, please contact LimitState support for assistance.

‘Scaling’ result

Scaling reduces the possibility of obtaining a solution of uncertain status due to numerical reasons. If the scaling fails to rectify the situation, the analysis will terminate and a solution status will be reported.

‘Slow Progress’ Result

Slow Progress is encountered when the solver is encountering difficulties in converging to an optimum solution. The solution returned in the current iteration may or may not be of acceptable quality. Therefore, the solution is shown with a strikethrough and a subsequent iteration is undertaken in order to attempt to fix the problem and return a good solution. If two consecutive ”Slow Progress” stages are returned by the solver then the solve is terminated.

‘Out of Space’ Result

The solver has exhausted all the available memory without achieving a converged solution. In such cases, it may be necessary to reduce the complexity of the problem or, more generally, increase the amount of RAM in the PC or switch to an operating system that provides a higher limit on the amount of memory that a process can utilize.

18.5.3 Aborting an Analysis

After the Mosek solver is started, LimitState:SLAB then waits for a solution to be found. To abort this process, the user should click on the red stop button ⏹ on the toolbar or press the **Esc** key to abort the analysis and return control to the user, which will occur at the next available time in the solution process.

18.5.4 Lock and Unlock

After a solution is found, the yield-line mechanism is displayed in the viewer window, and the solution is ‘locked’. A ‘locked’ solution prevents any modification to the problem geometry or properties, but allows access to the properties of individual yield-lines, pressure distributions on individual blocks and animation of the mechanism. It is possible to animate the mechanism (see Section 3.5), or click on individual yield-lines to determine normal and shear forces or stresses (see Section 3.6.2).

To allow editing of the problem parameters, click the unlock button 🔒 or select **Unlock** on the **Analysis** menu.

Chapter 19

Post-Analysis Functions

19.1 Collapse Mechanism

Following a successful solve, the collapse mechanism for the critical load case will be automatically displayed by the software (see Figure 19.1).

- **Positive** (sagging) yield-lines are displayed in **blue**.
- **Negative** (hogging) yield-lines are displayed in **red**.

The thickness of the yield-line denotes the amount of rotation that it is undergoing, relative to the other yield-lines in the solution. This allows the user to clearly isolate the primary failure mechanism and gain a deeper understanding of the way in which the slab is working.

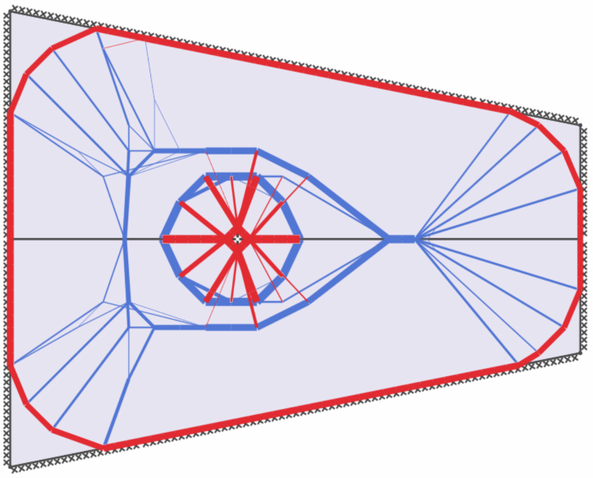


Figure 19.1: Yield-lines in a solved model - red denotes hogging while blue denotes sagging

19.2 Animation

LimitState:SLAB provides a useful facility to animate any failure mechanism to facilitate interpretation. To animate the mechanism following solve, use one of two options:

- Use the slider bar δ
- Click on the animate button 🎬

The animation may also be saved as an AVI or GIF file (Chapter 21). The preferences controlling the size and content of the file may be accessed via the ***Tools*** > ***Preferences*** menu under the ***Export*** tab (see Section 21.4).

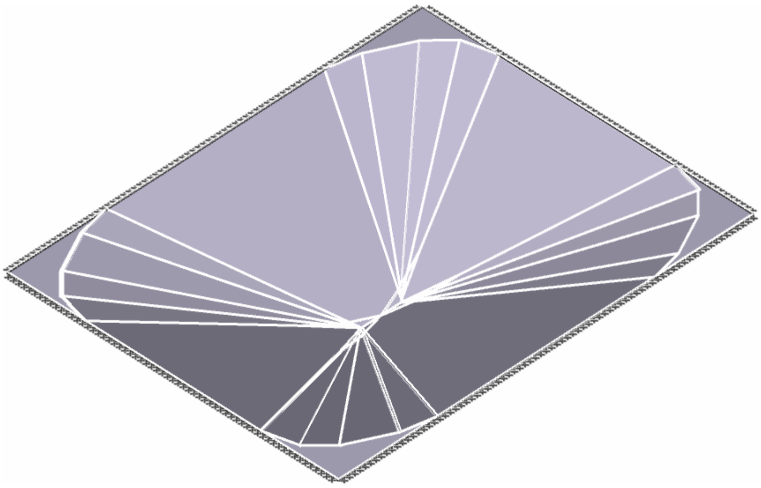


Figure 19.2: An animated LimitState:SLAB failure mechanism.

19.3 Yield-Lines

Following Solve and display of the solution, individual yield-lines and solid objects may be interrogated by selecting them with the mouse. The **Property Editor** will then display the following information:

ID - the name of the yield-line (internal)

Start node - x, y and z coordinates.

End node - x, y and z coordinates.

Length - the length of the yield-line.

Moment - the moment experienced along this section of yield-line.

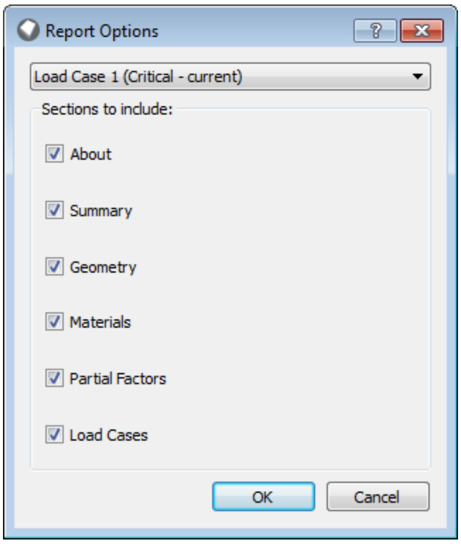
Rotation - the instantaneous relative rotation along the yield-line.

Chapter 20

Report Output

20.1 Viewing the Report Output

Following an analysis a customizable report can easily be generated. LimitState:SLAB can output a report in Microsoft Rich Text (.rtf) format which can then be edited if required by the user using a word processor. It is also possible to save the report in HTML format, e.g. for company intranet usage. To generate the report, on the **Analysis** menu click **Report...**: The following **Report options** dialog (Figure 20.1) allows full control over what is displayed in the report.



Load Case 1 (Critical - current)

Sections to include:

☑ About

☑ Summary

☑ Geometry

☑ Materials

☑ Partial Factors

☑ Load Cases

Figure 20.1: LimitState:SLAB **Report options** dialog.

20.2 Saving the Report Output

The report output from LimitState:SLAB can be saved to one of the following formats:

PDF Portable Document Format (.pdf)

RTF Rich Text Format (.rtf) - editable in most word processing software

HTML Hypertext Markup Language (.html)

To save the report, select **File** > **Save As...** in the report dialog.

20.3 Customizing the Header or Footer

Custom header and footer images can be included in the report by selecting the **Tools** menu, clicking **Preferences** and selecting the **Report** tab as shown in Figure 20.2.

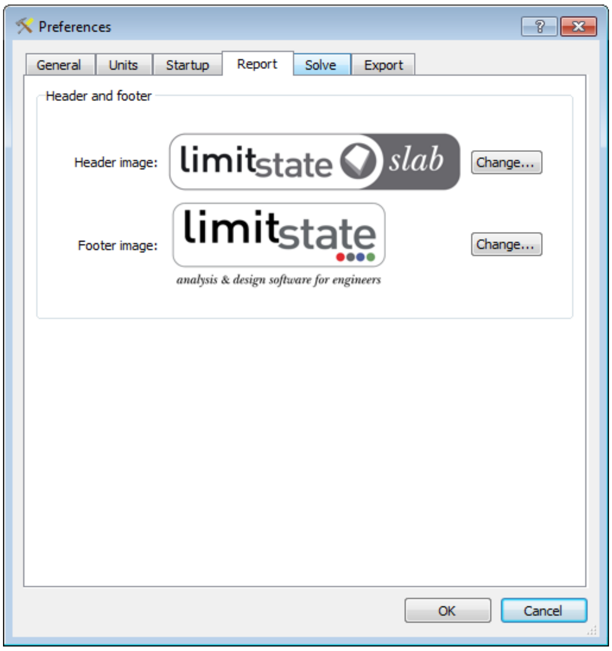


Figure 20.2: LimitState:SLAB report preferences.

Chapter 21

Exporting Graphical Output

21.1 Overview

LimitState:SLAB provides a number of options for exporting graphical output of the problem and the identified collapse mechanism. These may all be accessed from the main ***File/Export...*** menu as follows:

Geometry... This allows the geometry of the problem to can be saved as a Drawing Exchange Format (DXF) file for use in an external CAD package or import into a new LimitState:SLAB project. Alternatively the geometry can be saved as an Encapsulated PostScript (EPS) or Asymptote (ASY) file.

Image... This allows the image displayed in the **Viewer** pane to be saved as either a Portable Networks Graphics (PNG), Joint Photographic Experts Group (JPG), Tagged Image File Format (TIFF), Encapsulated PostScript (EPS) or Postscript (PS) file.

Animation... This allows an animation of the solved problem to be saved in either Graphics Interchange Format (GIF) or Audio Video Interleave (AVI) file formats.

21.2 Geometry Export

The original (unsolved) problem geometry may be saved as a DXF file for subsequent modification in a CAD package or for re-importing to LimitState:SLAB. This process is further described in Section 13.3.6.

The mechanism generated following solve may also be exported, along with the original geometry, as a line only vector graphics image (rather than a full color image) in either DXF - AutoCAD (.dxf), EPS - Encapsulated Postscript (.eps) or ASY - Asymptote (.asy) formats. Example output is shown in Figure 21.1 and may be contrasted with the ***Image*** output as shown in Figure 21.2. Where allowable, the different entities (nodes, geometry, failure mechanism etc. will be output to separate layers).

The Asymptote format is a script based graphical programming language. The output file provides a number of options for customising the image which can then be converted by Asymptote to a wide range of graphical output formats (e.g. EPS). The Asymptote file format can be viewed in any text editor and includes comments that may be consulted for further information.

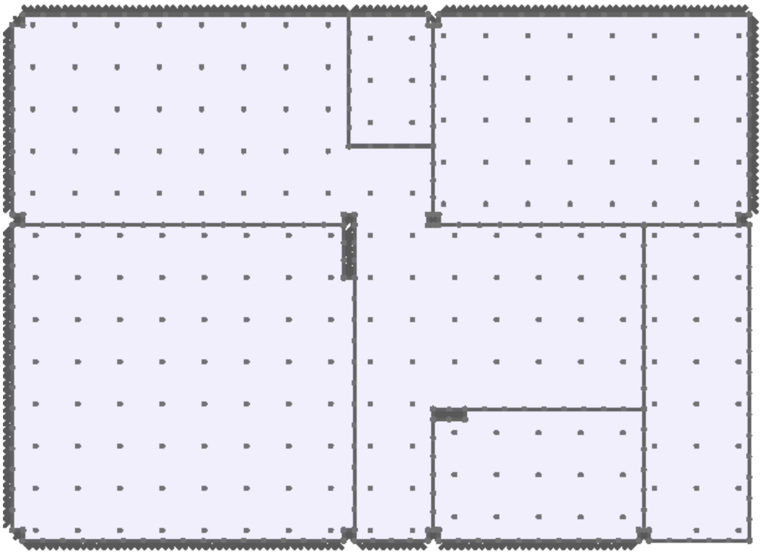


Figure 21.1: Example of line only vector graphics output for an example slab with columns.

21.3 Image Export

This function allows the image displayed in the **Viewer** pane (including displaced solutions) to be saved in one of the following formats:

PNG Portable Network Graphics raster image (.png)

JPG Joint Photographic Experts Group raster image (.jpg)

TIFF Tagged Image File Format (.tiff)

EPS Encapsulated Postscript vector image (.eps)

PS Postscript vector image (.ps)

An example raster image (.png) is shown in Figure 21.2.

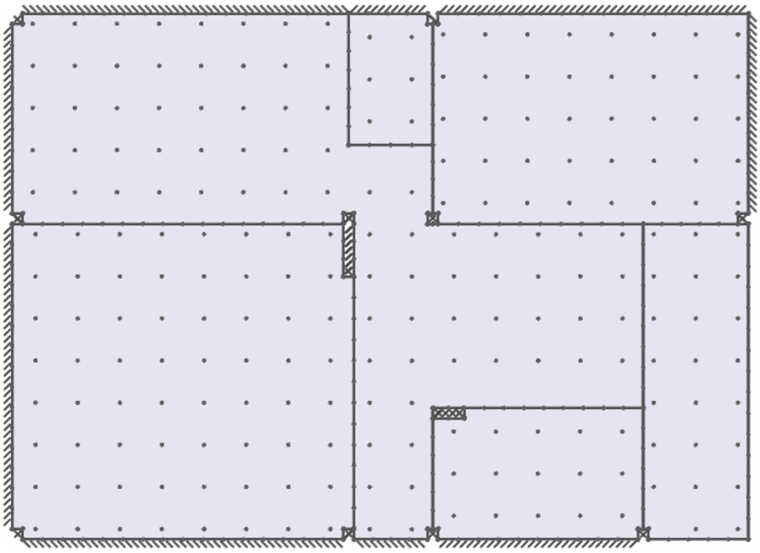


Figure 21.2: Example of image graphics output for an example slab with columns.

For raster images, the image width in pixels may be controlled using the ***Export*** tab in the ***Preferences*** dialog (accessed from the ***Tools*** menu) (see Figure 21.3).

21.4 Animation Export

An animation of the failure mechanism (as seen in the ***Viewer*** pane) can be exported to either:

AVI Audio Video Interleave (.avi)

GIF Graphics Interchange Format (.gif)

Both formats are readily incorporated into most modern Presentation packages.

To export an animation, go to the ***File*** menu and select ***Export...*** >***Animation...*** Here you can select the format of the file and save location.

The image width in pixels may be controlled using the ***Export*** tab in the ***Preferences*** dialog (accessed from the ***Tools*** menu) (see Figure 21.3).

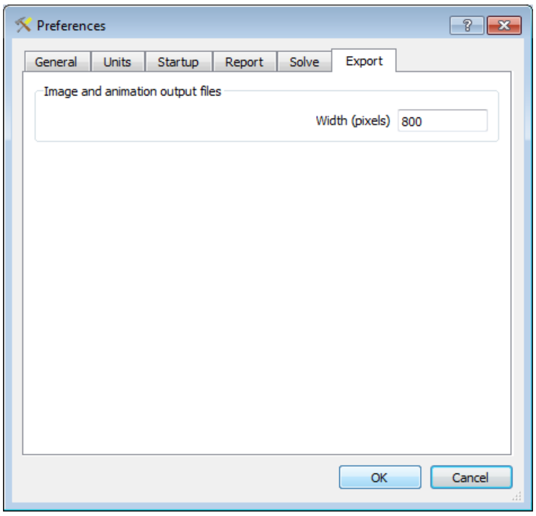

Preferences

Image and animation output files

Width (pixels) 800

Figure 21.3: Export settings for image and animation output.

An example animation (.avi) is shown in Figure 21.4.

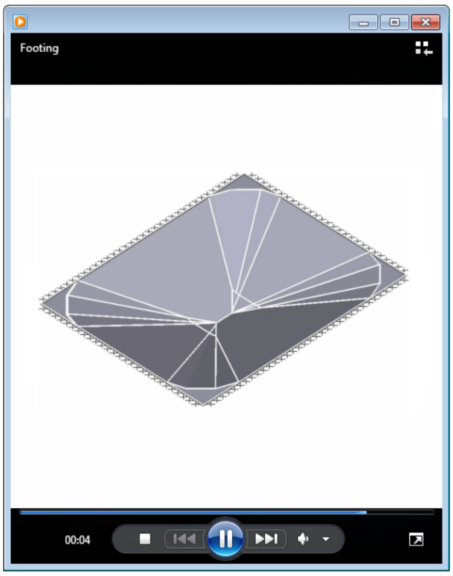


Figure 21.4: Animated failure mechanism from LimitState:SLAB

21.5 Animations and Multiple Load Case Problems

Where a problem involves more than one load case, the critical case is selected by default after solving and the image or animation relating to this will be exported. However, in some situations it may be desirable to export data relating to a non-critical case. To do this, simply select the tab at the bottom of the ***Viewer*** pane that relates to the case in question before exporting.

Part V

Appendices

Appendix A

Verification

A.1 Verification Tests

A list of tests carried out using LimitState:SLAB to verify its accuracy against known limit analysis solutions may be found at the following web page: http://limitstate.com/slab/validation.

These tests are run every time the software code is updated, and cover a broad range of geometries.

Generally, coarse numerical discretizations have been used, which enables solutions to be obtained relatively quickly on a desktop PC; the accuracy obtained is generally sufficient for engineering purposes, though improved (lower) load factors can generally be obtained if desired by using a finer numerical discretization.

In some cases it can be observed that LimitState:SLAB finds a failure mechanism and associated load factor which is lower than the compared benchmark (i.e. an improved solution is found). This is particularly noticeable when complex yield patterns are critical, which would be very difficult to find by hand.

Further details of each test including the source of the benchmark can be obtained by clicking on a hyperlink on the web page. The input file used to generate the test result may also be downloaded.

A.2 Academic Papers

The paper Smith & Gilbert 2007 includes a comparison of DLO solutions with known solutions.

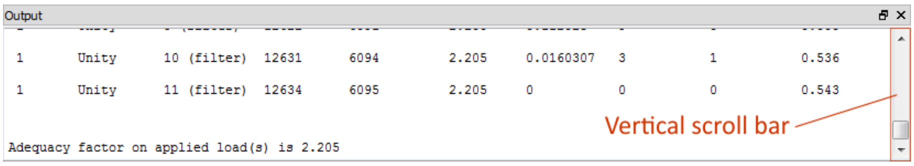
Appendix B

Menu and Toolbar Reference

B.1 General

B.1.1 Scrollbars

Vertical and horizontal scrollbars allow elements of the display area (e.g. the **Output Pane** to be shifted in the vertical and / or horizontal sense respectively dialog (Figure B.1).

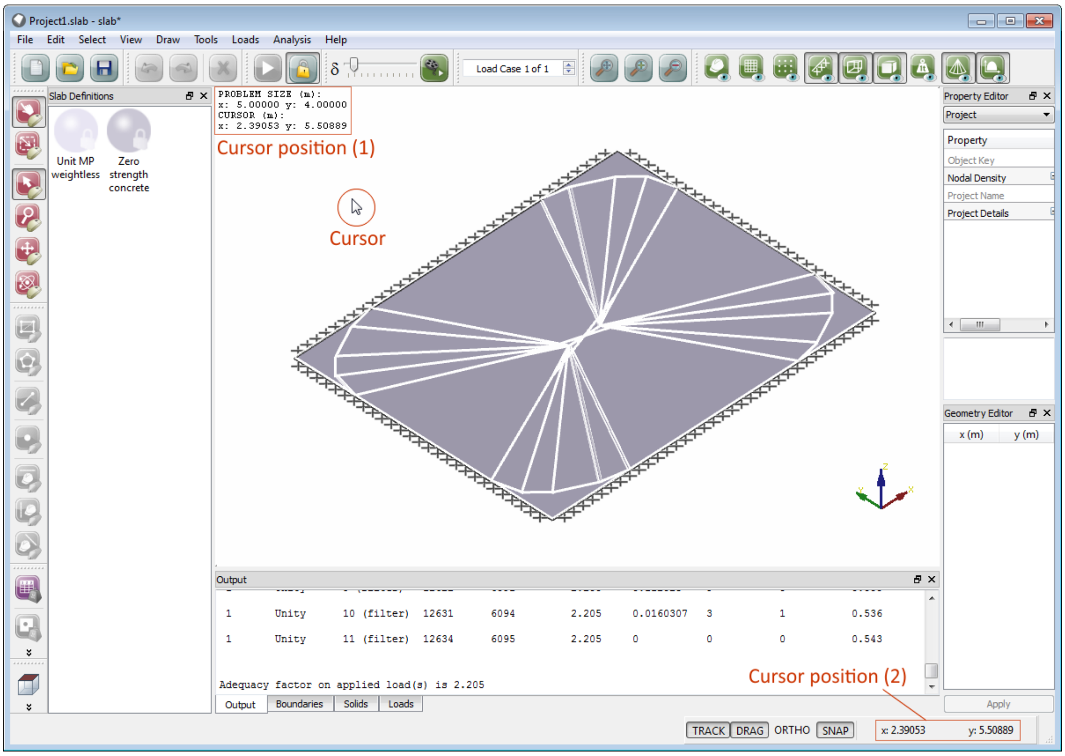


```
1        Unity      10 (filter)  12631      6094        2.205     0.0160307   3         1          0.536

1        Unity      11 (filter)  12634      6095        2.205     0           0         0          0.543


Adequacy factor on applied load(s) is 2.205
```

Figure B.1: Vertical scroll bar in the Output Pane

B.1.2 Cursor Position

The coordinates of the mouse are shown in the top left hand corner of the **Viewer Panen** the bottom right and also in the lower right corner of the screen on the **Status Bar** dialog (Figure B.2).



```
PROBLEM SIZE (m):
x: 5.00000 y: 4.00000
CURSOR (m):
x: 2.39053 y: 5.50889
```

```
1      Unity     10 (filter)  12631     6094       2.205     0.0160307  3         1         0.536
1      Unity     11 (filter)  12634     6095       2.205     0         0         0         0.543

Adequacy factor on applied load(s) is 2.205
```

x: 2.39053 y: 5.50889

Figure B.2: Cursor position

B.1.3 Scrolling Wheels

The third mouse button (where present) allows the user to pan and zoom the display:

- To **pan**, simply press and hold the third button whilst in the display window. The cursor will change to a cross and moving the mouse will pan the image around the screen.
- To **zoom**, simply roll the wheel up to zoom in and down to zoom out.

The pan and zoom functions are also accessible via the menu system described in Section B.3.1 and via keyboard shortcuts (see Section 3.6 and Section 3.7).

B.2 Menus

B.2.1 File Menu

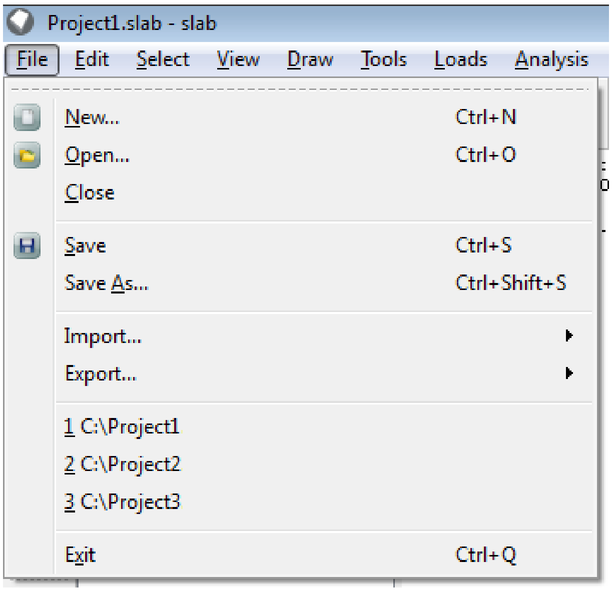
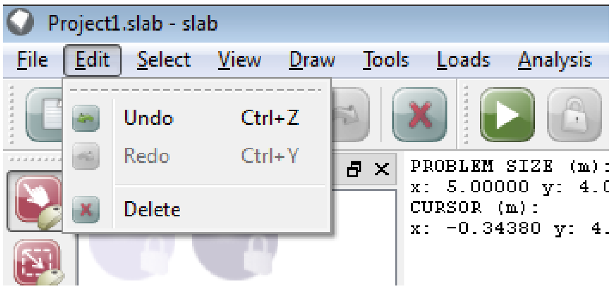


Figure B.3: The LimitState:SLAB File menu

Function	Shortcut	Description
New...	Ctrl+N	Create a new project.
Open...	Ctrl+O	Open an existing project.
Close		Close the current project.
Save	Ctrl+S	Save the current project.
Save As...	Ctrl+Shift+S	Save the current project under a specified name.
Import...		Import predefined *Slab Definitions* (Section 15.3) or problem *Geometry* (Section 13.3)
Export...		Export *Slab Definitions* (Section 15.3), problem *Geometry* (Section 13.3) or an *Image* (Section 21.3) or *Animation* (Section 21.4) of the model.
Open recent file		Open one of the 5 most recently accessed files.
Exit	Ctrl+Q	Exit LimitState:SLAB.

Table B.1: File menu functions

B.2.2 Edit Menu



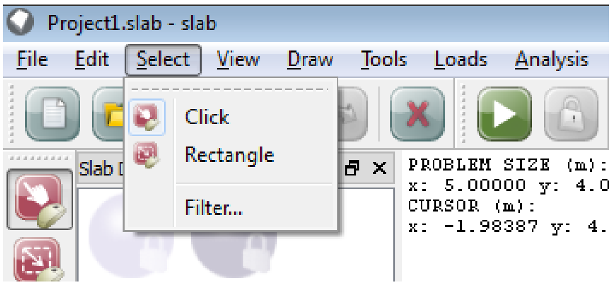
```
PROBLEM SIZE (m):
x: 5.00000 y: 4.(
CURSOR (m):
x: -0.34380 y: 4.
```

Figure B.4: The LimitState:SLAB Edit menu

Function	Shortcut	Description
Undo	Ctrl+Z	Step back to the point immediately before the last action was taken.
Redo	Ctrl+Y	Redo a previously undone action.
Delete		Delete the selected object(s).

Table B.2: Edit menu functions

B.2.3 Select Menu



```
PROBLEM SIZE (m):
x: 5.00000 y: 4.0
CURSOR (m):
x: -1.98387 y: 4.
```

Figure B.5: The LimitState:SLAB Select menu

Function	Shortcut	Description
Click		Select a single object (Section 14.4.1).
Rectangle		Select objects within a rectangular area (Section 14.4.2).
Filter...		Brings up the ***Selection Filter*** dialog (Section 14.4.2), allowing the user to select only *Vertices*, *Boundaries*, *Solids*, *Yield-lines* or a combination of these.

Table B.3: Select menu functions

B.2.4 View Menu

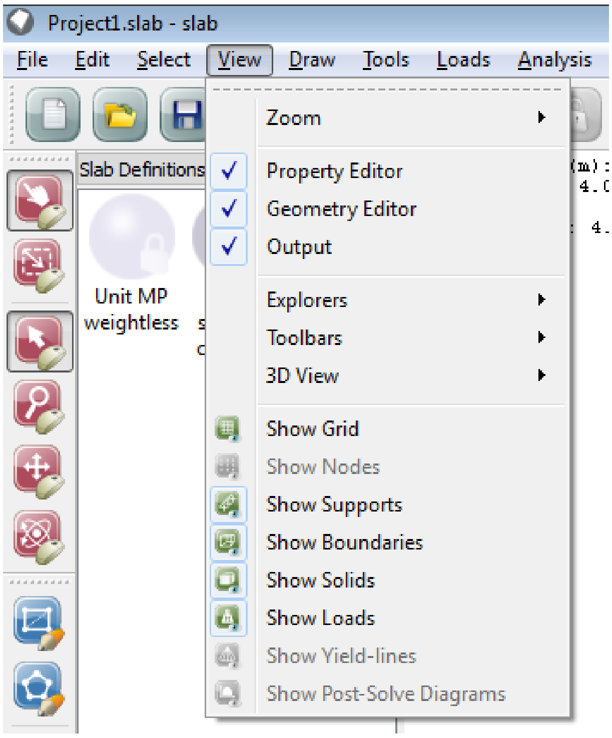


Figure B.6: The LimitState:SLAB View menu

Function	Shortcut	Description
Zoom ►		Access the zoom functions (Section 3.6).
Property Editor		Toggle the display of the **Property Editor** (Section 3.9 / Section 8.5).
Geometry Editor		Toggle the display of the **Geometry Editor** (Section 8.6).
Output		Toggle the display of the **Output** pane (Section 8.7).
Explorers ►		Toggle the display of the available **Explorers** (Section 8.9).
Toolbars ►		Toggle the display of the available **Toolbars** (Appendix B.3).
3D View ►		Choose from a variety of pre-defined 3D camera viewpoints or toggle the display of the global axis icon.
Show Grid		Toggle the display of the **Grid** (Section 13.2).
Show Nodes		Toggle the display of **Nodes** (***Solve*** or ***Preview Nodes*** must be executed before any effect is seen).
Show Supports		Toggle the display of **Supports** (i.e. Boundary Conditions) (Chapter 16).
Show Boundaries		Toggle the display of **Boundaries and Vertices** (Section 14.1).
Show Solids		Toggle the display of **Solids** (Section 14.1).
Show Yield-lines		Toggle the display of **Yield-lines**. Note ***Solve*** must be executed before any effect is seen).
Show Post-Solve Diagrams		Toggle the display of post-analysis force diagrams.

Table B.4: View menu functions

B.2.5 Draw Menu

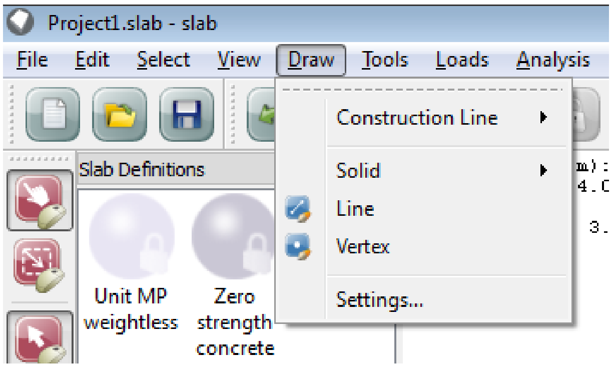


Figure B.7: The LimitState:SLAB Draw menu

Function	Shortcut	Description
Construction Line ▶		Display the **Construction Line** sub-menu (Section 14.2). From here you can *Draw* new construction lines or *Clear* the current set.
Solid ▶		Display the **Solid** drawing sub-menu (Section 14.3). From here you can create new *Rectangle* or *Polygon* solids.
Boundary		Draw a **Boundary** line linking two existing **Vertices** or **Boundaries** (Section 14.3.3).
Vertex		Add a **Vertex** to an existing **Boundary** line (Section14.3.4).
Settings...		Open the **Change Snap and Grid Settings** dialog.

Table B.5: Draw menu functions

B.2.6 Tools Menu

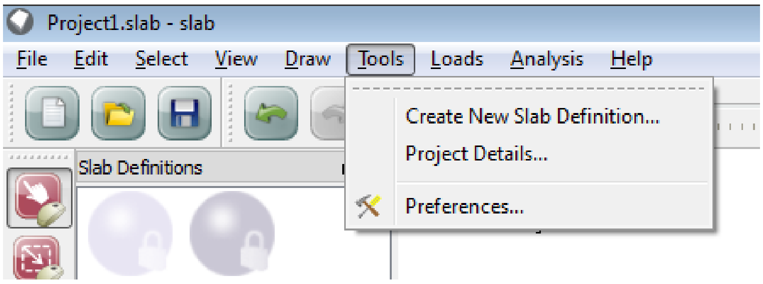

Project1.slab - slab
File Edit Select View Draw Tools Loads Analysis Help
Slab Definitions
Create New Slab Definition...
Project Details...
Preferences...

Figure B.8: The LimitState:SLAB Tools menu

Function	Shortcut	Description
Create New Slab Definition...		Open the **Create New Slab Definition** dialog (Section 15.2).
Project Details...		Open the **Project Details** dialog (Section 13.2.1).
Preferences...		Open the **Preferences** dialog, where project default settings can be specified (Section 11.1).

Table B.6: Tools menu functions

B.2.7 Loads Menu

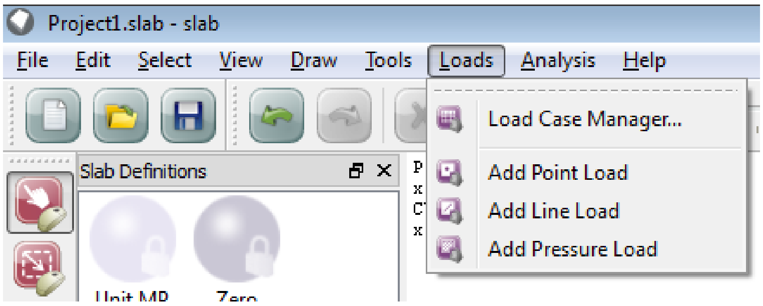


Figure B.9: The LimitState:SLAB Loads menu

Function	Shortcut	Description
Load Case Manager...		Open the **Load Case Manager** dialog (Section 17.3).
Add Point Load		Define the location and magnitude of a new point load within the **Viewer Pane** (Section 17.2.1).
Add Line Load		Define the location and magnitude of a new line load within the **Viewer Pane** (Section 17.2.2).
Add Pressure Load		Define the location and magnitude of a new pressure load within the **Viewer Pane** (Section 17.2.3).

Table B.7: Loads menu functions

B.2.8 Analysis Menu

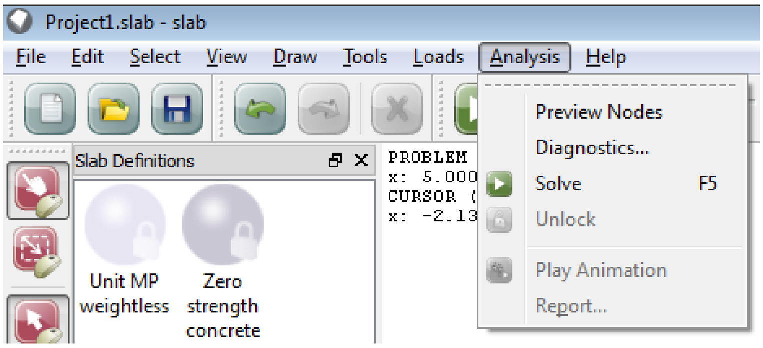


Figure B.10: The LimitState:SLAB Analysis menu

Function	Shortcut	Description
Preview Nodes		Preview nodes at the current nodal density setting without solving.
Diagnostics...		Open the **Diagnostics** dialog.
Solve	F5	**Analyse** the current problem (Section 18.3).
Unlock		Unlock the project for editing.
Play Animation		Animate the critical failure mechanism post solve (Section 19.2).
Report...		Open the analysis **Report** dialog (Chapter 20).

Table B.8: Analysis menu functions

B.2.9 Help Menu

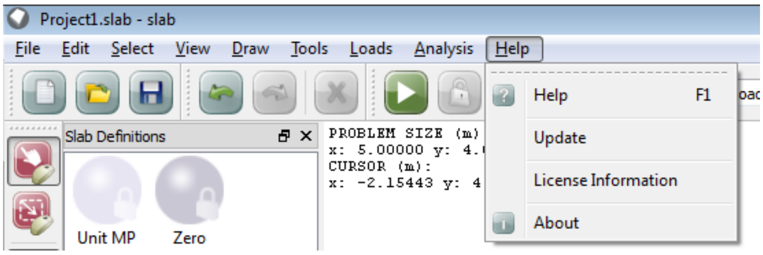


Figure B.11: The LimitState:SLAB Help menu

Function	Shortcut	Description
Help	F1	Open the **Help** dialog (Section 1.5).
Update		Check for updates to the software.
License Information...		Open the **License Information** dialog, which displays details of the license being used and allows the user to change to an alternative license (Chapter 12).
About		Display LimitState:SLAB version details.

Table B.9: Help menu functions

B.3 Toolbars

B.3.1 Default Toolbars

By default, the following toolbars are displayed when LimitState:SLAB is opened:

Toolbar	**Functions**
File	New / Open / Save (Appendix B.2.1).
Edit	Undo / Redo / Delete (Appendix B.2.2).
Cursor	Click / Rectangle / Select (Section 14.4). Zoom / Pan / Rotate 3D (Section 3.6 / Section 3.7).
Draw	Rectangle / Polygon / Line / Vertex (Section 14.3). Horizontal Construction Line / Vertical Construction Line / Custom Construction Line (Section 14.2).
Loads	Open Load Case Manager (Section 17.3). Add Point Load (Section 17.2.1) / Add Line Load (Section 17.2.2) / Add Pressure Load (Section 17.2.3).
Analysis	Solve / Unlock (Chapter 18). Analysis Type (Section 6.2).
Animation	Magnify Displacements / Play Animation (Section 19.2).
Zoom	Zoom All / Zoom In / Zoom Out (Section 3.6).
Show	Show Construction Lines / Show Grid (Section 14.2). Show Nodes / Show Supports / Show Boundaries (Chapter 16 / Section 14.1). Show Solids (Section 14.1) / Show Loads (Chapter 17) / Show Yield-lines (Section 19.1).
View 3D	View the problem from different angles: Top / Bottom / Left / Right / Front / Back

Table B.10: Default LimitState:SLAB toolbars

B.3.2 Optional Toolbars

To access some of the less commonly utilized features of LimitState:SLAB, it may be necessary to open a separate toolbar. To do this, click **View** and select **Toolbars**. The option to open the following is now available:

Toolbar	Functions
Rotate 3D	Rotate the problem in 3D or about different axes: Rotate 3D / Rotate About x / Rotate About y / Rotate About z
Help	Access: Help (Section 1.5) / About

Table B.11: Optional LimitState:SLAB toolbars

B.4 Context Menus

Depending upon the position of the cursor, right clicking the mouse within the LimitState:SLAB environment will bring up one of several context menus:

B.4.1 Viewer Pane Context Menu

Right-clicking within the **Viewer Pane** will bring up the following context menu:

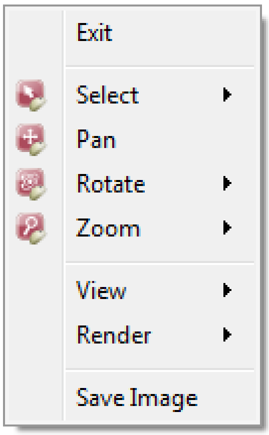


Figure B.12: Viewer Pane context menu

From here, you many of the display-related functions of the toolbars may be easily accessed, as well as several other independent functions:

Option	**Functions**
Exit	Exits the context menu.
Select	Switch between *Click* and *Rectangle* object selection (Section 14.4).
Pan	Pan the model in the **Viewer Pane** (Section 3.7).
Rotate	Rotate the view - either freely or about Cartesian axes (Appendix B.3.2).
Zoom	Activate Zoom mode or access the Zoom functions (Section 3.6).
View	Select a pre-defined 3D viewpoint, toggle 3D mode or toggle the Global Axis markers.
Render	Switch the quality of the rendering between *Normal*, *Low* and *High* resolution and *Rendered* or *Wireframe* modes. *High Render* resolution provides a crisper view but may slow the editing process on older or less powerful machines.
Save Image	Save the current view in raster or vector format (Section 21.3).

Table B.12: Viewer Pane context menu

B.4.2 Toolbar / Property Editor Context Menu

Right-clicking within any toolbar or **Property Editor** will display the menu shown in Figure B.13:

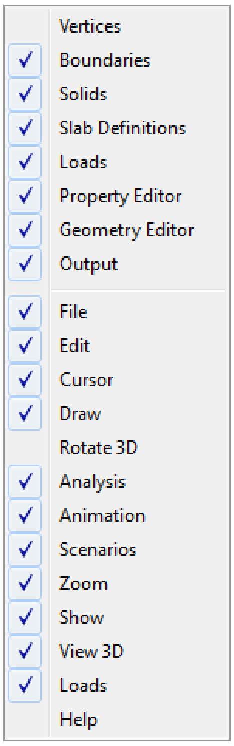


Figure B.13: Toolbar / Property Editor context contemenu

From here, you can toggle the display of the **Property Editor** (Section 8.5), **Output Pane** (Section 8.7), **Explorers** (Section 8.9) and **Toolbars** (Section 8.3).

B.4.3 Geometry Object Explorer Context Menu

Right-clicking within any geometry object **Explorer** (e.g. **Boundaries Explorer**, **Solids Explorer** or **Vertices Explorer**) will display the menu shown in Figure B.14:

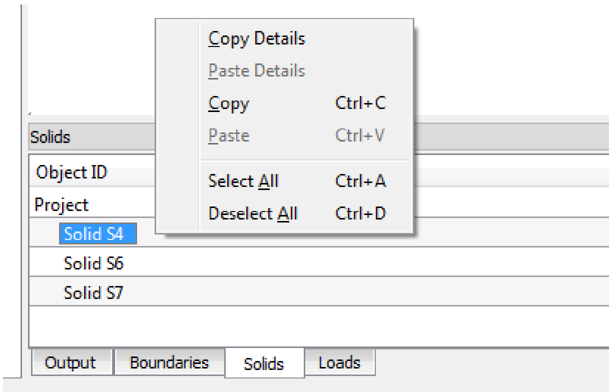


Figure B.14: Object Explorer context menu

From here, the functions described in Table B.13 are available:

Option	**Shortcut**	**Functions**
Copy Details		Copy the settings (i.e. row data) for the selected object.
Paste Details		Paste row data for the selected object.
Copy	CTRL+C	Copy data from the selected cells.
Paste	CTRL+V	Paste data to the selected cells (if a single cell is selected it will be treated as the top left cell and the data pasted accordingly.
Select All	CTRL+A	Select the entre table.
Deselect All	CTRL+D	Deselect the entire table

Table B.13: Geometry object Explorer context menu functions

Appendix C

Theoretical Basis

C.1 Discontinuity Layout Optimization

C.1.1 General Formulation

The general discretized kinematic DLO problem formulation may be stated as follows (after Smith & Gilbert (2007), Gilbert et al. (2014)):

$$\text{min } \lambda\mathbf{f}_{\mathrm{L}}^{T}\mathbf{d} = -\mathbf{f}_{\mathrm{D}}^{T}\mathbf{d} + \mathbf{g}^{T}\mathbf{p} \tag{C.1a}$$

subject to:

$$\mathbf{Bd} = \mathbf{0} \tag{C.1b}$$

$$\mathbf{Np} - \mathbf{d} = \mathbf{0} \tag{C.1c}$$

$$\mathbf{f}_{\mathrm{L}}^{T}\mathbf{d} = 1 \tag{C.1d}$$

$$\mathbf{p} \geq \mathbf{0} \tag{C.1e}$$

Or alternatively as an equivalent ‘equilibrium’ formulation (derived using duality principles) as:

$$\text{max } \lambda \tag{C.2a}$$

subject to:

$$\mathbf{B}^{T}\mathbf{t} + \lambda\mathbf{f}_{\mathrm{L}} - \mathbf{q} = -\mathbf{f}_{\mathrm{D}} \tag{C.2b}$$

$$\mathbf{N}^{T}\mathbf{q} \leq \mathbf{g} \tag{C.2c}$$

where λ is a dimensionless load factor, $\mathbf{f}_{\mathrm{D}}$ and $\mathbf{f}_{\mathrm{L}}$ are vectors respectively prescribing specified dead and live load effects, $\mathbf{d}$ contains displacements along the discontinuities, $\mathbf{B}$ is a suitable compatibility matrix and $\mathbf{N}$ is a suitable flow matrix. Finally, $\mathbf{p}$ and $\mathbf{g}$ are vectors of plastic multipliers and their corresponding work equation coefficients and $\mathbf{t}$ and $\mathbf{q}$ are vectors of equivalent nodal forces and forces along discontinuities respectively.

In the kinematic formulation the discontinuity displacements in $\mathbf{d}$ and the plastic multipliers in $\mathbf{p}$ are the linear programming (LP) variables, whereas in the corresponding equilibrium formulation the equivalent nodal forces in $\mathbf{t}$, the forces along discontinuities in $\mathbf{q}$, and the load factor λ are the LP variables.

Given that (C.1) and (C.2) only express general relations, it is now necessary to identify appropriate variables for the slab problem now being studied, starting by considering the kinematic formulation.

C.1.2 Kinematic Formulation for Slabs

Considering the kinematic problem formulation for slabs, the contributions of a given yield-line i to the global compatibility constraint equation (C.1b) can be written as:

$$\mathbf{B}_i\mathbf{d}_i = \begin{bmatrix} \alpha_i & -\beta_i & 0 \\ \beta_i & \alpha_i & 0 \\ 0 & \frac{l_i}{2} & 1 \\ -\alpha_i & \beta_i & 0 \\ -\beta_i & -\alpha_i & 0 \\ 0 & \frac{l_i}{2} & -1 \end{bmatrix} \begin{bmatrix} \theta_{\mathrm{n}i} \\ \theta_{\mathrm{t}i} \\ \delta_i \end{bmatrix} \tag{C.3}$$

where $\theta_{\mathrm{n}i}$, $\theta_{\mathrm{t}i}$ and δ_i are respectively the normal rotation along a potential yield-line, the twisting rotation, and the out-of-plane displacement, and where α_i and β_i are x-axis and y-axis direction cosines. Note that the signs of the displacement variables in $\mathbf{d}_i$ are unrestricted since additional non-negative plastic multiplier variables will ensure positive energy dissipation.

Suppose that there exists no coupling between normal and twisting rotations, and between the shear displacement along a yield-line. In this case the contributions of a given yield-line i to the global flow rule constraint (C.1c) can be written as:

$$\mathbf{N}_i\mathbf{p}_i - \mathbf{d}_i = \begin{bmatrix} 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & -1 \end{bmatrix} \begin{bmatrix} p_i^1 \\ p_i^2 \\ p_i^3 \\ p_i^4 \\ p_i^5 \\ p_i^6 \end{bmatrix} - \begin{bmatrix} \theta_{\mathrm{n}i} \\ \theta_{\mathrm{t}i} \\ \delta_i \end{bmatrix} \tag{C.4}$$

However, at a typical yield-line it can generally be assumed that the torsional (twisting) and out-of-plane displacements, $\theta_{\mathrm{t}i}$ and δ_i respectively, will be zero, and hence these variable can be omitted from the formulation, along with their corresponding plastic multiplier variables, p_i^3, p_i^4, p_i^5 and p_i^6. This situation does not apply at free boundaries however, where $\theta_{\mathrm{t}i}$ and δ_i should be free to take on arbitrary values. i.e. such variables should be added to signal the presence of such a boundary. Similarly at a line of symmetry, δ_i should be free to take on an arbitrary value.

C.1.3 Equilibrium Formulation for Slabs

Considering the equilibrium problem formulation for slabs, the required equilibrium constraint can be written for a potential yield-line discontinuity i as follows:

$$\mathbf{B}_i^T \mathbf{t}_i + \lambda \mathbf{f}_{\mathrm{L}i} - \mathbf{q}_i = -\mathbf{f}_{\mathrm{D}i} \tag{C.5}$$

or, in expanded form as:

$$\begin{bmatrix} \alpha_i & \beta_i & 0 & -\alpha_i & -\beta_i & 0 \\ -\beta_i & \alpha_i & \frac{l_i}{2} & \beta_i & -\alpha_i & \frac{l_i}{2} \\ 0 & 0 & 1 & 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} m_A^x \\ m_A^y \\ t_A^z \\ m_B^x \\ m_B^y \\ t_B^z \end{bmatrix} + \lambda \begin{bmatrix} m_{\mathrm{Ln}i} \\ m_{\mathrm{Lt}i} \\ f_{\mathrm{L}i} \end{bmatrix} - \begin{bmatrix} M_{\mathrm{n}i} \\ M_{\mathrm{t}i} \\ S_i \end{bmatrix} = - \begin{bmatrix} m_{\mathrm{Dn}i} \\ m_{\mathrm{Dt}i} \\ f_{\mathrm{D}i} \end{bmatrix} \tag{C.6}$$

where m_j^x, m_j^y and t_j^z can be interpreted respectively as x and y direction equivalent nodal moments and an out-of-plane nodal force, all acting at a given node j, and where $M_{\mathrm{n}i}, M_{\mathrm{t}i}$ and S_i represent respectively the yield-line moment, torque and shear force acting on discontinuity i (see Figure C.1). Finally, $m_{\mathrm{Dt}i}, m_{\mathrm{Dt}i}, f_{\mathrm{D}i}$ and $m_{\mathrm{Lt}i}, m_{\mathrm{Lt}i}, f_{\mathrm{L}i}$ represent the dead and live load effects as applied to discontinuity i.

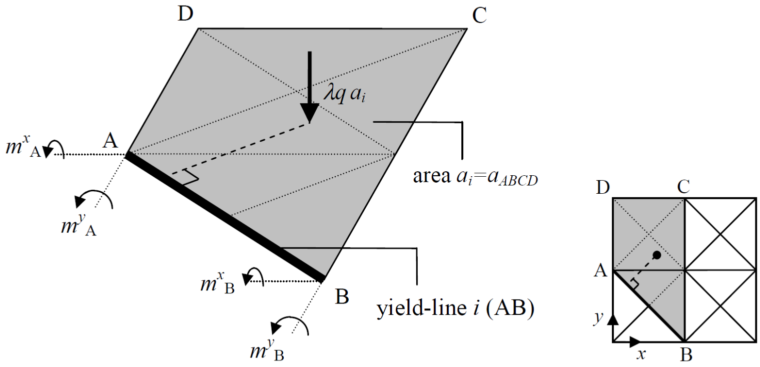


Figure C.1: Nodal moments at the ends of yield-line i (AB)

Now considering the contribution of a given yield-line i to the global yield constraint (C.2c), initially assuming that N_i is as defined in equation (C.4):

$$\mathbf{N}_i^T \mathbf{q}_i = \begin{bmatrix} 1 & 0 & 0 \\ -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} M_{\mathrm{n}i} \\ M_{\mathrm{t}i} \\ S_i \end{bmatrix} \leq \begin{bmatrix} m_i^{p+} \\ m_i^{p-} \\ m_{ti}^{p+} \\ m_{ti}^{p-} \\ s_i^{p+} \\ s_i^{p-} \end{bmatrix} \tag{C.7}$$

Although at a typical yield-line the inequality equation (C.7) reduces simply to $m_i^{p-} \leq M_{\mathrm{n}i} \leq m_i^{p+}$, by inspection it is clear that more complex yield functions could be introduced if required, for example involving interaction between the normal and torsional moments (though in doing so the traditional 'yield-line' character of the solution is likely to be lost, e.g. a twisting failure is likely to lead to loss of contact between the two ends of the slab adjoining a given yield-line).

C.1.4 Adaptive Solution Procedure

While LimitState:SLAB utilizes the core methodology described above, it also makes use of an adaptive solution procedure described by Gilbert & Tyas (2003) in order to significantly reduce memory requirements and also reduce the time needed to obtain a solution. The procedure makes use of the fact that the solution identified by the linear programming solver can be used to determine the moment, torque and shear force acting on any yield-line connecting any pair of nodes, even if the solver did not explicitly consider that yield-line in determining its solution. In essence the procedure operates as follows:

1. Set up an initial 'ground state' in which nodes are connected by yield-lines only to nearest neighbour nodes vertically, horizontally and diagonally.
2. Solve this problem utilising the DLO procedure. This will give a valid upper bound solution, but of relatively low accuracy, utilising only these short yield-lines.
3. Utilizing this solution, search through all potential yield-lines connecting every node to every other node and determine whether yield is violated on any potential yield-line.
4. If yield is violated on a potential yield-line, add this yield-line to the linear optimization problem set and re-solve. Repeat from Stage 3.
5. If yield is not violated on any yield-line then the correct solution has been arrived at, as if all possible yield-lines had been included in the original linear programming problem.

C.2 Extensions to the Basic DLO procedure

C.2.1 Treating Non-Convex Problem Domains

Real-world slab-geometries will often more complex, e.g. comprising complex non-convex problem domains. Although such geometries present no particular difficulties for conventional element-based formulations, various issues arise when the DLO procedure is applied. These will now be explored.

C.2.1.1 Inter-nodal Connections in Non-Convex Problem Domains

Consider the non-convex slab (ABCDEFGHIJ) shown on Figure C.2. If it is assumed that each node is connected to every other node by potential yield-lines, it is evident that some potential yield-lines (e.g. the highlighted yield-line BH on C.2(a)) cross 'free space'. Perhaps the most obvious way of dealing with this situation is to simply compute a mean moment of resistance per unit length for this (notional) potential yield-line; however this approach leads to certain

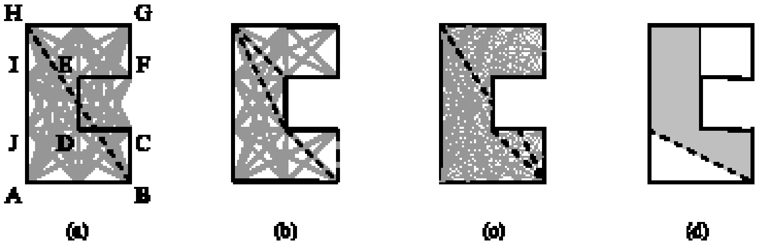


Figure C.2: Slab with non-convex 'C' shaped geometry: (a) potential yield-lines, with critical yield-line BH which crosses domain boundaries highlighted; (b) reduced set of potential yield-lines with alternatives to BH highlighted; (c) as (b) but with finer nodal spacing along edges; (d) area to consider when formulating $\mathbf{f}_L$ term for potential yield-line BJ

complications and it has been found to be more convenient to simply disallow such potential yield-lines. However, this does mean that a good representation of previously well represented potential yield-lines may not be achievable (e.g. see C.2(b)). To help compensate for this it has been found to be beneficial to use a finer nodal discretization along all boundaries, C.2(c).

Since there are large numbers of potential yield-lines to consider (e.g. for a problem involving $10,000$ nodes there will be $\frac{10{,}000(10{,}000-1)}{2}$ = 49,995,000 potential yield-lines), it is vitally important that checks whether a potential yield-line passes through 'free space' or not are carried out in computationally efficient manner; various ways of doing this are possible - in the software this is achieved by allocating appropriate 'bit fields' to each node, with a potential connection between a pair of nodes then being introduced according to the outcome of a simple logical bitwise operation.

C.2.1.2 Computing Load Effects in Non-Convex Problem Domains

It is also necessary to consider how the load terms in $\mathbf{f}_\mathrm{L}$ and $\mathbf{f}_\mathrm{D}$ should be computed when a non-convex slab is involved. Thus referring to C.2, suppose that the slab has material properties, support and loading conditions which mean that at failure part of the slab (BCDEFGHIJ) rotates as a rigid element about a single yield-line BJ, i.e. as indicated in C.2(d). Assuming both dead and live loads are involved, it is instructive to consider how the components in $\mathbf{f}_{\mathrm{L}i}$ and $\mathbf{f}_{\mathrm{D}i}$ can be calculated for i = BJ. In this case, as only the area shaded will be directly influenced by rotation along BJ, only loading within this shaded area need be accounted for in the calculations. The remaining unshaded area lying 'above' potential yield-line BJ will clearly also move in the mechanism postulated, but the work associated with this movement will be accounted for through displacement along edge EF (combined translation and rotation), with the relative displacements at the edge of the slab in effect being absolute displacements.

C.2.2 Definition of Mp Directions

For reinforcement at an angle α to the global X axis, the moment resistance it contributes is taken normal to the reinforcement, as shown in Figure C.3.

In LimitState:SLAB, users must specify the angle of the moment resistance (i.e. β) in addition

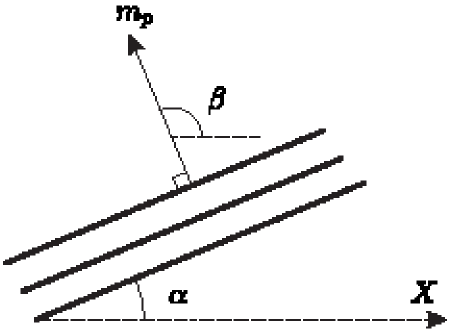


Figure C.3: Direction of the moment capacity regarding reinforcement angle

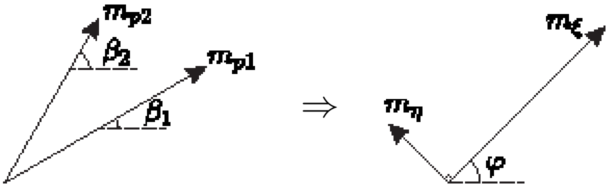


Figure C.4: Transforming skew reinforcement to an equivalent orthogonal layout

to the Mp values.

C.2.3 Orthotropic Reinforcement

For orthotropic reinforcement, the formula described in Johansen (1962, p.52) is used. Assume an orthogonal reinforcement layout $\xi - \eta$, the moment resistance at an angle θ to ξ axis is derived using:

$$m_p^\theta = m_\xi \cos^2\theta + m_\eta \sin^2\theta \tag{C.8}$$

C.2.4 Skew Reinforcement

In case of skew reinforcement, the method described in Johansen (1962, p.55-56) and Nielsen & Hoang (2011, p.67-69) is adopted. Assume the moment resistance in direction 1 is at angle β_1 and in direction 2 at angle β_2. Denote $\beta_1 - \beta_2$ the skew layout. An equivalent orthogonal reinforcement layout $\xi - \eta$ is derived so the problem is tackled as an orthotropic slab. Figure C.4 describes such transformation.

The orthogonal layout $\xi - \eta$ is at an angle φ that can be derived from:

$$\tan 2\varphi = \frac{\sum_{i=1}^{2} m_{pi}\sin 2\beta_i}{\sum_{i=1}^{2} m_{pi}\cos 2\beta_i} \tag{C.9}$$

And the moment resistance in $\xi - \eta$ can be calculated using:

$$m_\xi = \frac{1}{2}\left(\sum_{i=1}^{2} m_{pi} \pm \sqrt{(\sum_{i=1}^{2} m_{pi}\cos 2\beta_i)^2 + (\sum_{i=1}^{2} m_{pi}\sin 2\beta_i)^2}\right) \tag{C.10}$$

$$m_\eta = \frac{1}{2}\left(\sum_{i=1}^{2} m_{pi} \mp \sqrt{(\sum_{i=1}^{2} m_{pi}\cos 2\beta_i)^2 + (\sum_{i=1}^{2} m_{pi}\sin 2\beta_i)^2}\right) \tag{C.11}$$

Appendix D

Accessing Example Files

To open the specified example file, locate it in:

[ROOT]/example files/

where **[ROOT]** is the installation path of LimitState:SLAB, usually:

C:/Program Files/LimitState/SLAB2.3.1 /

Alternatively, open the Example Files html page from the LimitState:SLAB program menu and open the file from there:

Start > All Programs > LimitState:SLAB 2.3.1 > Example Files.

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