LARSA 2000/4th Dimension: Staged Construction Analysis



LARSA 2000/4th Dimension: Staged Construction Analysis

for

LARSA 2000
Finite Element Analysis and Design Software

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Revised August 2004

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Introduction

Staged Construction Analysis analyzes a series of construction steps, which represent the steps in the evolution of a structure's construction, demolition, or rehabilitation. The Staged Construction Analysis is a form of nonlinear static analysis [see "Nonlinear Static Analysis" in *LARSA 2000 Reference*] that retains the state of the structure from step to step, automatically applying construction activities specified by the user. Staged Construction Analysis makes scenario testing an automated process.

Changes to a structure over time are defined in a series of construction steps. Construction steps can include construction activities, such as constructing parts of the structure, applying loads, and modifying support conditions. Time-effects on material behavior, including the effect of super-imposed loads, can be automatically accounted for.

Because the Staged Construction Analysis is a nonlinear analysis, geometric nonlinearity is included, a necessary feature for any structure with nonlinear elements, such as cables.

Staged Construction Analysis comes in two types. In the Standard type, a Nonlinear Static Analysis [in *LARSA 2000 Reference*] is performed for each construction step, retaining the deformed properties of the structure from step to step. Time-effects on materials are ignored. In the Time-Dependent type, the same nonlinear analysis is performed, but Time Effects on Materials [p28] are included.

Elements are activated and deactivated through their inclusion in construction activities, which is explained in Setting Up the Model [p13]. When a Staged Construction Analysis begins, LARSA assumes no elements have been activated. Only elements explicitly constructed in construction activities contribute to the stiffness of the structure. If the structure is to start off constructed, the first construction activity should assemble the structure into its constructed state.

A structure can change over time any number of ways in the real world. LARSA supports the following construction activities:

- **Construction**: Parts to the structure are added (assembled). Joint locations can be automatically adjusted based on the deformed shape of the structure according to contruction methods, a necessary tool for segmental projects such as balanced cantilever bridges.
- **Deconstruction**: Parts of the structure are removed (disassembled)
- **Weight and Stiffness**: Self-weight and stiffness can be activated in different steps.
- **Supports**: Joints are restrained or released (globally or slaved to other joints)
- **Loads**: Loads are applied or removed
- **Tendons**: Stressed or slackened
- **Materials**: Creep and shrinkage for concrete, and relaxation for steel (see Time Effects on Materials [p28])
- *Structural elements cannot change connectivity*

Staged construction often comes hand-in-hand with pre- and post-tensioning elements. Such tensioning is generally accomplished with tendons, which are discussed in the tendons section of the Bridge Analysis manual [see "Tendons" in *LARSA 2000/4th Dimension: Bridge Analysis*] and in the tendons section in the Model Data Reference [see "Tendons" in *LARSA 2000 Reference*].

Structural Changes over Time

LARSA is able to model continuous changes to a structure over time involving a useful set of construction activities.

Structural changes occur in a serial or linear fashion. An example of staged construction might be . . .

1. Construct Left Pier
2. Construct Right Pier
3. Construct Center Temporary Pier (modeled as fixing center joint in space)
4. Construct Span from Left to Temporary Pier
5. Construct Span from Right to Temporary Pier
6. Stress Tendons
7. Deconstruct Temporary Pier (modeled as releasing center joint)

Each of those steps is refered to as a *construction activity*.

Preparation

Before defining construction activities in LARSA,

1. All elements in the structure that will ever be assembled must be modeled.

   Structures should be modeled as if every member, plate, and spring used at any point during construction are all present at the same time. The time at which elements are constructed will be specified later.

   As a result, all joints that will ever be a part of the model must be in the project. Joints are automatically included in the model when elements attached to it become constructed and are automatically removed from the model when all attached elements are deconstructed.

Tendons [see "Tendons" in *LARSA 2000 Reference*] and other structural objects must also be entered before proceeding on to modeling construction activities.

2. Restraints must be set to initial conditions

   Joints will be initially restrained as their restraints are specified in the project, taking into account standard restraints [see "Joints" in *LARSA 2000 Reference*] and slave/masters [see "Slave/Master Constraints" in *LARSA 2000 Reference*].

3. Groups of elements that will be constructed or deconstructed together should be put into structure groups [see "Structure Groups Explorer" in *LARSA 2000 User's Guide*].

   Although structure groups need not be defined ahead of time, it will save time later.

The steps outlined from this point on assume that the above tasks have been completed.

Construction Activities

Construction activities are specified in two ways, using the Construction Stages Explorer or the Construction Stages Editor. This section will outline the general process. A later section [p13] describes how to use the two methods.

LARSA arranges construction activities into **stages** and **steps**.

Stages

A stage represents one day of construction, which can consist of one or more steps. Stages are labeled with a day number, a temperature and a humidity value, which apply to all steps within the stage. The day of the stage is used for computing time-effects on materials.

Steps

A step represents one set of construction activities to accomplish a goal. Steps occur within stages. All construction activities occur within steps.

Both stages and steps can be given descriptive names.

Example:

1. Piers (Day 1)

1. Left Side

- Construct Left Pier
- Load Left Pier

2. Right Side

- Construct Right Pier

2. Center (Day 12)

1. Center

- Fix Center Joint
- Load Center Joint

3. Spans (Day 14)

1. Span 1

- Construct Span 1 Part 1
- Construct Span 1 Part 2

2. Span 2

- Construct Span 2

3. Tendon

- Stress Tendon

4. Remove Center (Day 30)

1. Remove Center

- Release Center Joint

The example to the right shows how the sample at the top could be arranged into stages (Piers, Center, Spans, Remove Center) and steps (Left Side, Right Side, Center, Span 1, Span 2, Tendons, Remove Center). Note how the stages and steps form a simple hierarchy.

The construction activities that can be placed within steps are

Construction/Deconstruction

Structural elements are constructed or deconstructed. Constructed elements are used in the analysis of the structure. Deconstructed elements are ignored. Elements start off ignored until they are constructed.

The part of the structure that is constructed/deconstructed in a particular construction activity is determined by a structure group [see "Structure Groups Explorer" in *LARSA 2000 User's Guide*]. The construction/deconstruction of one structure group is a single construction activity.

Elements may be constructed in locations relative to the deformed state of the structure. The Accounting for Deformation [p24] and joint displacement initialization (below) are used to specify such behavior. Normally, elements are constructed in the position that they are initially defined in.

Support Change

A support's properties have changed, or a joint is becoming a support. Support activities specify the new restraints of a joint [see "Joints" in *LARSA 2000 Reference*] in all six degrees of freedom.

Slave/Master Change

A joint's [see "Joints" in *LARSA 2000 Reference*]slave/master [see "Slave/Master Constraints" in *LARSA 2000 Reference*] connectivity is changed. Slave/Master activities specify the new slave/master connections of a joint. Old slave/master connections in all degrees of freedom are discarded for a joint whenever a new slave/master activity for that joint is encountered.

Load Application

A static load case [see "Static Load Cases" in *LARSA 2000 Reference*] is applied to the structure. A loading factor can be specified. For instance, a loading factor of 2 will multiply the magnitudes of all loads in the load case by 2 when applying them to the model in that step.

Loads are applied **cumulatively**; that is, a load applied in one stage will automatically continue to be applied in all future stages. To "turn off" a load, apply the load again with a negative load factor. The one exception to the rule is self weight: A self-weight load case must be included in any stage where new elements are constructed so that self weight will be applied to those new members. (LARSA will never apply self weight multiple times to an element.)

Tendon Application

A tendon [see "Tendons" in *LARSA 2000 Reference*] is stressed or slackened.

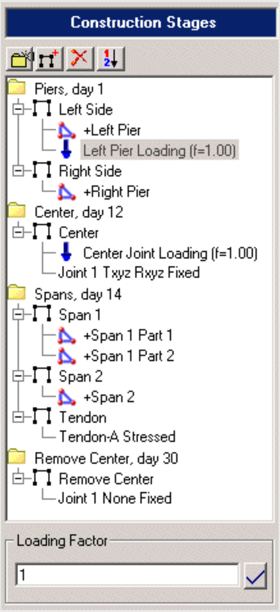
Displacement Initialization

Alters the initial location of a joint. Normally, when joints are activated they enter at the location that was initially given to them. Joints sometimes need to become active in a location relative to the deformed structure of the model, rather than in an exact position known ahead of time. Displacement Initializations specify how to place a joint relative to the deformed location of other joints. They are explained in more detail in a later section [p24].

Setting Up the Model

Construction activities are specified in two ways, using the Construction Stages Explorer or the Construction Stages Editor. This section explains how to use each method.

Creating Activities in the Explorer



Construction Stages Explorer

The Construction Stages Explorer presents the construction stages and steps in the same style as the example above. A screenshot is on the right.

For more information on the meaning of each type of construction activity, see Structural Changes over Time [p8].

Using the Explorer:

- To open the Explorer if it is not already open, right click the title bar area of the open Explorer (where it reads "Construction Stages" in the figure) and choose *Construction Stages*.
- To **add a construction stage**, click the Add Stage button, which looks like a folder. A new stage will be added to the bottom of the list of stages. Each stage is labeled with the day on which its steps' activity occurs, which is "day 0" by default.
- To **add a construction step** to the project, select the stage in which to add the new step, and then click the Add Step button, which looks like a small frame.
- To **delete** a stage or step, select the stage or step and then click the Delete button, which looks like an X.
- To **rename** a stage or a step, select the stage or step, and then hit `F2`. Type the new name, and then hit `Enter`.
- If after adding various stages they have become out of **chronological order**, click the Sort button. The stages will be sorted by Day.

Preparing for Time Effects in the Explorer:

- To include **time-effects on materials** in construction analysis, each construction stage must have a time assigned, determined by a stage's Day. To edit a stage's day, select the stage. Then, make the change in the text box at the bottom of the explorer. Hit the checkmark to finalize the change.
- To modify the **humidity or temperature** of a stage, which is used to compute time-effects on materials in construction analysis, open the Load Groups & Stages spreadsheet window, which can be found in the **Input Data** menu. Select the Construction Stages tab. This spreadsheet will show a list of the stages added to the project, but not the construction steps.

Adding Construction Activities in the Explorer:

- If part of the structure is to be **constructed or deconstructed** in a step, click and drag a Structure Group [see "Structure Groups Explorer" in *LARSA 2000 User's Guide*] of those elements from the Structure Groups Explorer onto the step in the Construction Stages Explorer during which they will be constructed.

  To see the two Explorers at once, double-click the title bar area of the open Explorer (where it reads "Construction Stages" in the figure). The right click the title area of the Explorer on the bottom and choose *Structure Groups*. Double click the title area of the top Explorer again to close the lower Explorer.

  Structure groups in a step must be either all constructed or all deconstructed. Use multiple steps if both construction and deconstruction will occur.

  If that structure group is to be **deconstructed**, right-click the construction step (not the group). Click **Properties** and choose the *Deconstruct* option. The step will become a deconstruction step, indicated by a red X through the step's icon.

  Structure groups can be constructed in **weight-only mode** in which the self-weight of the group is applied to the structure but the group adds no stiffness to the structure. This is useful when a concrete member is poured but not immediately hardened. To specify that a structure group be weight-only, right click the group and select *Weight Only*. To have the group contribute stiffness in a later stage, add the group to the Construction Stages Explorer again, but without the weight-only option.
- Static **load cases** are be applied during a step by dragging a load case from the Load Cases Explorer [see "Load Cases Explorer" in *LARSA 2000 User's Guide*] onto the step in the Construction Stages Explorer during which the load case should be applied. To see the two Explorers at once, see the previous point.
- **Other activities** are accessed

- Using the Construction Stage Editor, which is explained below, or
- Through spreadsheets [see "Using the Model Spreadsheets" in *LARSA 2000 User's Guide*]. To add these activities to a step, right-click the step and then select **Support, Slave, Tendon Activity**.

Creating Activities in the Stage Editor

The construction stage editor is an alternative way of building/editing the stage construction data in LARSA 2000. Unlike the Construction Stages Explorer, the Construction Stage Editor uses a spreadsheet based approach to orginize the data.

The spreadsheet does not only contains the data but also some commands with a self explanatory label to their functionality. These commands can be easily distinguised by their red, italic, underlined format. Double clicking on these commands will activate them.

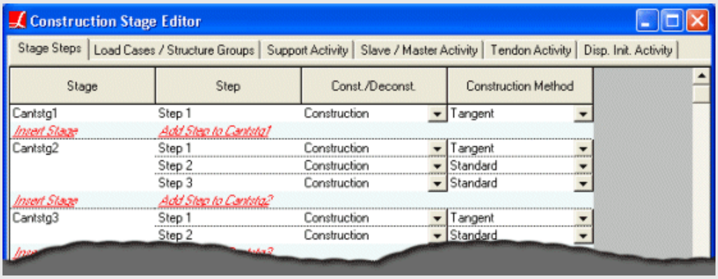
Each spreadsheet contains the commands to add, remove, and rename stages and steps.

The dialog box is composed of six tab menus. Each menu represents a type of spreadsheet. Below you find the explanation on each tab menu and how it is being used.

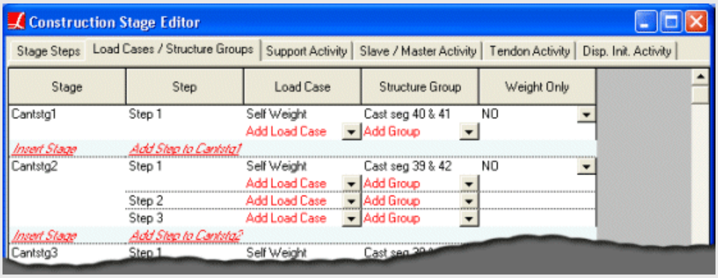
For more information on the meaning of each type of construction activity, see Structural Changes over Time [p8].

On the **Stage/Steps** spreadsheet, you can:

- Add, remove, and rename stages and steps,
- Specify whether each step is for construction or deconstruction, and
- Define the segmental construction method [p24] of each step. Unless your model needs to update joint locations to account for deformation, the Standard method should be chosen.



Construction Stage Editor: Stage Steps

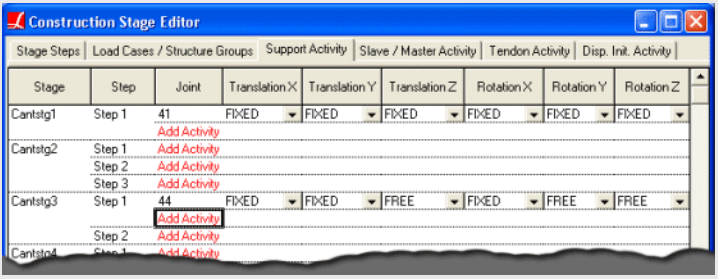


Construction Stage Editor: Load Cases / Structure Groups

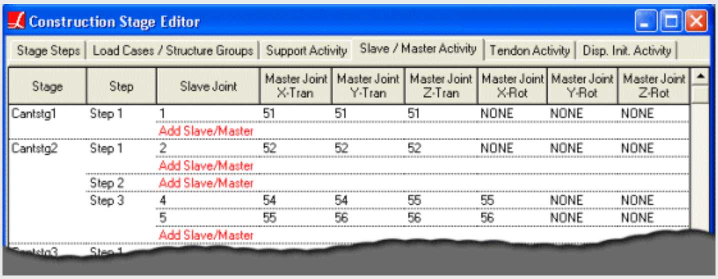
On the **Load Cases/Structure Groups** spreadsheet, you can :

- Add and remove load cases to steps,
- Add and remove geometry groups to steps, and
- Specify whether geometry groups are weight-only. (For an explanation of weight-only groups, see the previous section.)

On the **Support Activity** spreadsheet, you can add or remove support activity for each step by specifying the joint number and six degrees of fredom.



Construction Stage Editor: Support Activity

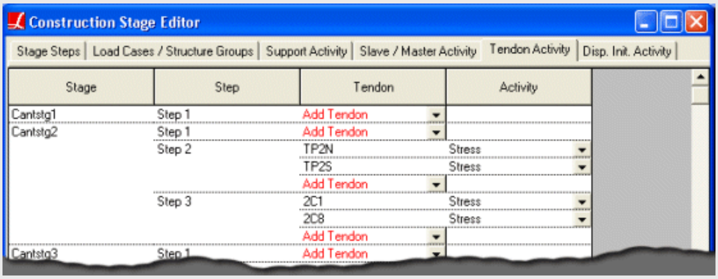


Construction Stage Editor: Slave/Master Activity

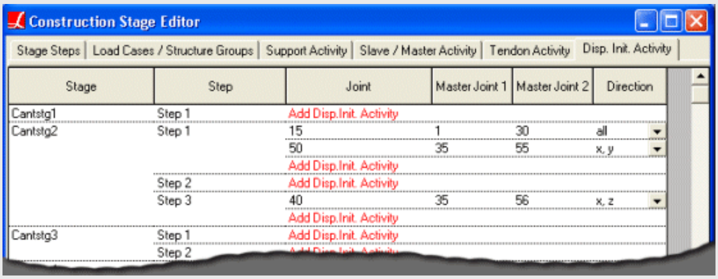
On the **Slave/Master Activity** spreadsheet, you can add and remove slave/master activity for each step by specifying the joint number and the master joint at six degrees of fredom.

On the **Tendon Activity** spreadsheet, you can

- Add and remove tendon activity for each step, and
- Specify whether each tendon is stressed or slackened.



Construction Stage Editor: Tendon Activity



Construction Stage Editor: Displacement Initialization Activity

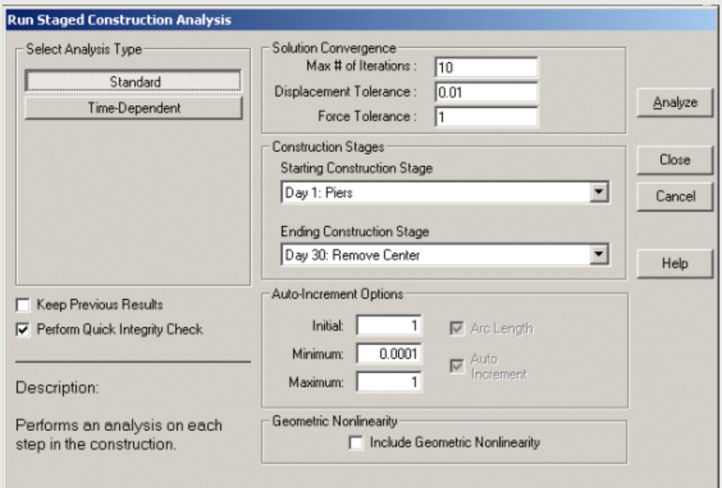
On the **Displacement Initialization Activity** spreadsheet, you can add and remove displacement initialization activities for each step by specifying the joint number that the initialization process will take place, the joints at both ends, and the adjustment direction.

Running a Staged Construction Analysis

The steps in this section describe how to run a staged construction analysis.

If you will be including time-effects on materials, please read the section Time Effects on Materials [p28] to see how to set those options.

To perform a Staged Construction Analysis, click the **Analysis** menu and choose *Staged Construction Analysis*.



Running a Staged Construction Analysis

Then choose the analysis options.

Choose the type of analysis: Standard or Time Dependent. (For the difference between the two, see Introduction [p6].)

Because the Staged Construction Analysis is a derivative of the nonlinear static analysis, the analysis shares some of the same options, which are explained below. In addition, the Standard analysis may perform plastic pushover analyses at certain stages. Plastic pushover's auto-increment options for those steps are explained below.

Click *Analyze* to run the analysis.

Construction Stages

Choose which construction stages are to be analyzed. The analysis can only pick up from any stage up to where it last left off, or from the start.

Starting Construction Stage
The stage that the analysis will begin at.

Ending Construction Stage
The stage that the analysis will stop at.

Solution Convergence

Equilibrium iterations at a given load level can cease when the result is "close enough" according to one or more criteria. Two criteria used in LARSA are that the unbalanced force be a small fraction of the total applied force in the current load level and that the current displacement increment be a small fraction of the displacement increment. The convergence criteria are specified by the user as the displacement tolerance, force tolerance and maximum number of iterations. The iterative analysis continues untill all degrees of freedom in the model satisfy displacement and force tolerance criteria within the maximum number of iterations.

If the solution is not convergent for a load step, a message is displayed on the screen. If there are additional load steps, analysis will continue if the structure is not unstable. LARSA carries the unbalanced forces into the next load step and a convergent solution may be obtained in the next load step. This may imply that your structure is fine and you either have to increase the maximum number of iterations or use a less restrictive error ratio.

Max # of Iterations

The number of iterations performed for each load step will not exceed the maximum number of iterations specified by the user. We recommend 10 to 20 as a maximum number of iterations.

Displacement Tolerance

The displacement tolerance is the error ratio of the incremental displacement computed in the last iteration divided by the total displacement for the same degree of freedom. The default value is 0.001 (0.10%).

Force Tolerance

The force tolerance is the maximum unbalanced force at any degree of freedom.

Auto-Increment Options

The pushover analysis is based on automatically incrementing the load vector. Specify here the multipliers for the load vector that will be used in computing the initial load vector and the incremental load vector limitation.

Initial

This is the factor multiplying the load vector for computing the load to be applied on the structure in the first load step.

Minimum

The minimum factor multiplying the load vector that is used in any load step. When the iterative analysis requires reduction in the magnitude of the load vector, the multiplier cannot be smaller than this value.

Maximum

The maximum factor multiplying the load vector that is used in any load step.

Geometric Nonlinearity

Choose whether geometric nonlinear will be included in the analysis.

Include Geometric Nonlinearity

Whether geometric nonlinear will be included in the analysis

For More Information

- For help on running an analysis, see Running an Analysis [in *LARSA 2000 User's Guide*].

Accounting for Deformation

Normally, when joints are activated they enter at the location that was initially given to them. Joints sometimes need to become active in a location relative to the deformed structure of the model, rather than in an exact position known ahead of time. The segmental construction method option of construction steps and joint displacement initialization activities specify how to place a joint relative to the deformed location of other joints.

Segmental Construction Method

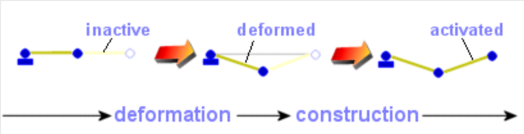
The segmental construction method option of construction steps specifies that the locations of all joints becoming active in the step will be updated acording to a segmental construction rule.

The example below shows why a special segmental construction method might be necessary. It is a simple segmental bridge built in stages.

In the first stage, only the left segment is activated.

After the application of loads, the segment deforms. The center node is displaced, but the right node is left unchanged because inactive joints are ignored in the analysis.

As a result, when the next segment is constructed, the segments form an angle, even though there was no angle when the segments were initially modeled. This may not be the desired model.



A Use for Segmental Construction Method

Two other behaviors might have been desired:

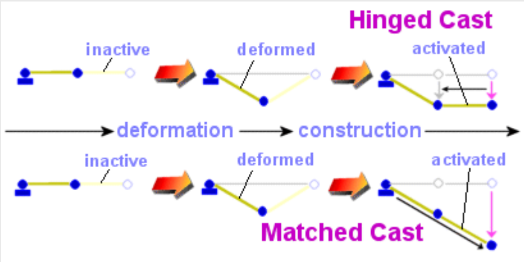
Hinged Cast

The next segment should be constructed by shifting the end node down to match the translational displacement of the center node. i.e. The segment was drawn horizontal, and it should remain horizontal.

Matched Cast

The next segment should be constructed by shifting the end node down to match the angular displacement of the center node. i.e. The segment was drawn parallel to the last, and it should remain parallel.

These are shown in the figure below.



Hinged Cast versus Matched Cast

Displacement Initializations

Displacement initialization construction activities specify that a joint's location should be updated to be mid-way between two other joints.

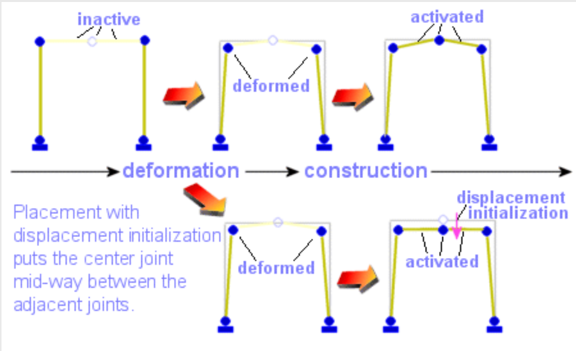
The example below shows why displacement initializations might be necessary. It is a simple frame with a two-member span at the top, but it is built in stages.

In the first stage, only the columns are activated.

After the application of loads, the structure deforms. The upper-left and upper-right nodes are displaced, but the top-center node is left unchanged because inactive joints are ignored in the analysis.

As a result, when the beams are constructed, they form an angle. This may not be the desired model.

In this structure, the joint should be initialized mid-way between the adjacent nodes after those nodes have been deformed. A displacement initialization construction activity can specify this behavior.

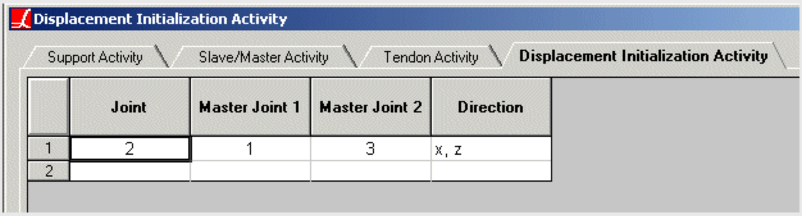


A Use for Displacement Initializations

When a joint is given a displacement initialization, its location is adjusted so that it falls midway between two other joints.

For the example above, the center joint should be given a displacement initialization in the step during which the joint becomes activated. The displacement initialization should reference the adjacent nodes.

Displacement initializations are entered in the spreadsheet displayed below.



Creating a Displacement Initialization

In the figure, joint 2's position will be updated so that it is mid-way between joint 1 and joint 3 in its x- and z-coordinates. The update will take place at the start of the step in which this displacement initialization has been added.

Time Effects on Materials

Time effects on materials account for concrete creep and shrinkage, steel creep and relaxation, and other material changes.

Conventional analyses fails to accurately account for material properties which change over time. Concrete is subject to creep and shrinkage.Steel is subject to relaxation, and in fire it is subject to creep as well. These changes and elastic modulus variation are accounted for in LARSA's time-dependent staged construction analysis.

Time-dependent deformation of concrete resulting from creep and shrinkage is of crucial importance in the design of prestressed concrete structures because these changes result in a partial loss of prestress force with significant changes in deflections.

Concrete creep and shrinkage, tendon relaxation, the time-effect on elastic modulus are based on the prediction models and equations from FIP-CEB90 and FIP-CEB78, AASHTO, ACI, BS5400-4, BS8110-2 codes or user-defined material property curves for time-dependent behavior.

Time-Dependent Stage Construction Analysis requires time, temperature, and humidity conditions. To set time, temperature, and humidity conditions, see Setting Up the Model [p13].

Definitions

The following time-dependent material effects can be computed by LARSA. Which effects to include are specified in options, which are explained below.

Concrete Creep

Creep is the property of many materials by which they continue deforming over considerable lengths of time at constant stress or load.

Creep strain for concrete depends not only time, but on the mix proportions, humidity, curing conditions and the age of concrete when it is first loaded. The rate of strain increase is rapid at first, but decreases with time until a constant value is approached asymptotically.

Concrete Shrinkage

Normal concrete mixes contain more water than is required for hydration of the cement where the free water evaporates in time. Drying of concrete is accompanied by a reduction in volume. The rate of drying depends on the humidity, ambient temperature, and the size and shape of the concrete element and the change in volume occurs at a higher rate initially.

Steel Relaxation

When prestressing steel is stressed to the levels that are customary during initial tensioning and at service loads, it exhibits a property known as relaxation. Relaxation is defined as the loss of stress in a stressed material held at a constant length. This same phenomenon is known as creep when defined in terms of change in length of a material under constant stress. In prestressed concrete members, creep and shrinkage of the concrete as well as fluctuations in superimposed loads cause change in tendon length. Relaxation is not a short-lived phenomenon, it continues almost indefinitely, although at a diminishing rate.

Relaxation must accurately be accounted for in the design because it produces significant loss of prestress force. The amount of relaxation varies depending on the type and grade of steel, but most significant parameters are time and intensity of the initial stress.

Prestressing tendons are held stressed at essentially constant length during the lifetime of a member, although there is some reduction in length due to concrete creep and shrinkage and superimposed loads. There will be a gradual reduction of stress in the steel under these conditions resulting from relaxation, even though the length is held nearly constant.

The amount of relaxation depends on the intensity of steel stress as well as time and, for stress-relieved steel, the ratio of stress to initial stress.

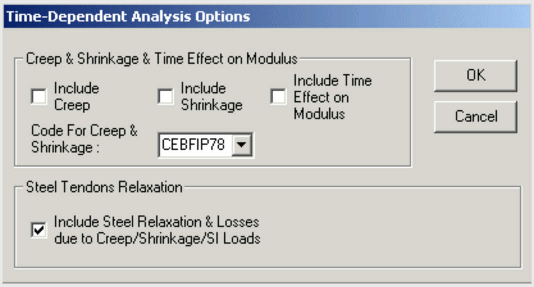
Time Effect on Modulus of Elasticity

The strength of concrete varies significantly from initial days to day 28, although from day 28 on the variation is very slow. This variation of strength is caused by changes to the elastic modulus. LARSA can vary the elastic modulus of concrete materials according to several codes.

The Effect of Creep, Shrinkage, and Superimposed Loads on Post-Tensioning

Concrete creep and shrinkage and other loads applied after a tendon is stressed (superimposed loads) generate strain, which alters the forces in the post-tensioning. Relaxation curves (explained below) must be entered into the LARSA project and assigned to any materials that will undergo relaxation, and those materials must be assigned to the tendons.

General Options



Setting Time-Dependent Analysis Options

To set these options, open the **Analysis** and choose **Time-Dependent Analysis Options**.

Include Creep

If checked, concrete creep computations are included in the analysis. Creep is applied to all members with materials that have a *concrete cement hardening type* set to anything except *Not Concrete*. (See Materials [in *LARSA 2000 Reference*].)

Include Shrinkage

If checked, concrete shrinkage computations are included in the analysis. Creep is applied to all members with materials that have a *concrete cement hardening type* set to anything except *Not Concrete*. (See Materials [in *LARSA 2000 Reference*].)

Include Time Effect on Modulus

If this option is not checked, LARSA uses the elastic modulus specified for each material [see "Materials" in *LARSA 2000 Reference*] at all time points. If this option is checked, the elastic modulus supplied by the material is treated as the value on day 28.

Code for Creep & Shrinkage

Determines which material model will be used for computing time-dependent material properties.

CEBFIP78

This code uses a user-defined material model based on the CEBFIP78 guidelines. Use this option to supply custom curves for special environmental conditions. This code requires the following time-dependent material curves [see "Time-Dependent Material Property Definitions" in *LARSA 2000 Reference*] to be entered by the user:

- Concrete Shrinkage Curve
- Concrete Delayed Plastic Strain Curve
- Concrete Delayed Elastic Strain Curve
- Stress/GUTS vs. Relaxation Curve
- Time vs. Relaxation Curve
- Time versus Elastic Modulus Curve: This curve cannot be directly entered by the user. LARSA uses pre-defined equations.

CEBFIP90

This code requires the following time-dependent material curves [see "Time-Dependent Material Property Definitions" in *LARSA 2000 Reference*] to be entered by the user:

- Stress/GUTS vs. Relaxation Curve

- Time vs. Relaxation Curve

  This code has built-in equations for the computation of creep and shrinkage coefficients and therefore does not require the following curves to be entered by the user.

- Concrete Shrinkage Curve
- Concrete Delayed Plastic Strain Curve
- Concrete Delayed Elastic Strain Curve
- Time versus Elastic Modulus Curve

Include Steel Relaxation & Losses due to Creep/Shrinkage/SI Loads

When this option is checked, prestressing losses in tendons from steel relaxation are included. In addition, reduction in prestressing will be computed from the effects of concrete creep and shrinkage and other loads applied after the tendon is stressed (superimposed loads). Relaxation curves (explained above) must be entered into the project and assigned to any materials that will undergo relaxation, and those materials must be assigned to the tendons.

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