Advanced Application 3

Completed State and Construction Stage Analyses of a Suspension Bridge



CONTENTS

Introduction	1	
Procedure for Completed State Analysis		2
Bridge Dimensions		3
Completed State Analysis Modeling	4	
Structural Modeling		4
Assign Working Environment		5
Define Material Properties		6
Define Section Properties		7
Initial Equilibrium State Analysis		9
Divide pylon elements to create pylon transverse beams		13
Input Boundary Conditions		17
Define Structure Groups		23
Input loadings		25
Suspension Bridge Analysis Control		27
Remove Nonlinear Analysis Control Data and Suspension Bridge Analysis	3 Data	30
Remove and Modify Beam End Release Conditions for Deck		32
Input Load Cases and Static Loads		35
Perform Structural Analysis (Completed State Analysis)	37	
Review Results of Completed State Analysis Static Analysis Results	38	38
Modeling for Construction Stage Analysis	45	
Assign Working Environment	40	46
Define Construction Stage Names		47
Assign Structure Groups		48
Assign Boundary Groups		56
Define Construction Stage Loads and Load Groups		61
Define Construction Stages		62
Input Construction Stage Analysis Data		69
Perform Structural Analysis (Construction Stage Analysis)	69	
Review Construction Stage Analysis Results	70	
Review Deformed Shape		70
Review moments		74
Review axial forces		75
Review deformed shape using animation		77

Introduction

Suspension bridges can generally be classified as long span structures. Suspension bridges comprise longitudinal deck (main girders) supported by hangers suspended from cables. The cables are connected to anchors at each end.

The analysis of a suspension bridge is divided into completed state analysis and construction stage analysis.

The *completed state analysis* is performed to check the behavior of the completed bridge. At this stage, the structure is in balance under self-weight, and the deflection due to the self-weight has already occurred. This stage is referred to as the initial equilibrium state of the suspension bridge. The initial equilibrium state analysis will provide the coordinates and tension forces in the cables. The completed state analysis of the suspension bridge is performed to check the behavior of the structure under additional loads such as live, seismic and wind loadings. The self weight loading in the initial equilibrium state will also be added to the total loading for the completed state analysis.

Suspension bridges exhibit significant nonlinear behavior during the construction stages. But it can be assumed that the bridge behaves linearly for additional loads (vehicle, wind load, etc.) in the completed state analysis. This is due to the fact that sufficient tension forces are induced into the main cables and hangers under the initial equilibrium state loading. It is thus possible to perform a linearized analysis for the additional static loads at the completed state by converting the tension forces in the main cables and hangers resulting from the initial equilibrium state loading into increased geometric stiffness of those components. This linearized analytical procedure to convert section forces to geometric stiffness is referred to as the *linearized finite displacement method*. This procedure is adopted because a solution can be found with relative ease within acceptable error limits in the completed state analysis.

Construction stage analysis is performed to check the structural stability and to calculate section forces during erection. In carrying out the construction stage analysis, large displacement theory (geometric nonlinear theory) is applied in which equilibrium equations are formulated to represent the deformed shape. The effect of large displacements cannot be ignored during the construction stage analysis. The construction stage analysis is performed in a backward sequence from the state of equilibrium as defined by the initial equilibrium state analysis.

This tutorial explains the overall modeling and result analyzing capabilities for the completed state and construction stage analyses of a suspension bridge.







Fig. 1 Analytical Model

Bridge Dimensions

The example model is a suspension bridge having a total length of 650m as shown in Fig. 1. Detailed bridge dimensions are shown in Fig. 2.



Fig. 2 General Profile

Completed State Analysis Modeling

Structural Modeling

In this tutorial, the suspension bridge modeling sequence is as follows. First, create the model for the completed state analysis, perform completed state analysis, and then create the construction stage analysis model under a different name.

The suspension bridge modeling procedure for the completed state analysis is as follows:

- 1. Define material and section properties
- 2. Analyze initial equilibrium state (using Suspension Bridge Wizard)
- 3. Create a model and enter boundary conditions
 - Divide pylon (tower) members to generate pylon transverse beams
 - Create & remove pylon transverse beams
 - Enter boundary conditions
- 4. Accurate initial equilibrium state analysis
 - Define structure groups
 - Enter self weight
 - Perform analysis
- 5. Input static loads & modify boundary conditions
- 6. Perform completed state analysis

Assign Working Environment

Open a new file (New Project), save as "Suspension Bridge .mcb" (Save) and assign a unit system.

💽 / 🗅 New Project / 🖶 Save (Suspension Bridge)

Tools / ^{Unit} **System** (alternatively select from the status bar at the bottom of the screen)

Length>m; Force> tonf ↓

Unit System		×		
-Length	Force (Mass)	Heat		
⊙ m	C N (kg)	C cal		
C cm	C kN (ton)			
C mm	C kgf (kg)	L 0		
C ft	tonf (ton)	Сю		
Cin	C kips (kips/a)	C Btu		
Celsius C Fahrenheit				
Note : Selected units are displayed in relevant dialog boxes. Values are NOT changed with units.				
Set/Change Default Unit System				
OK Apply Cancel				

Fig. 3 Assign unit system

In this tutorial, 3-dimensional analysis will be performed.

Define Material Properties

Input material properties for cable, hanger, deck (main girder) and pylon.

Properties / Material Properties Material Name>Cable Type>User Defined	
Modulus of Elasticity (2.0e+7)	
Weight Density (8.267) →	
Properties X Material Section Thickness ID Name Type 1 Cable User Def. 2 Hanger User Def. 3 Deck User Def. 4 Pylon User Def. Copy Import Renumber	Material Data • considered • considered
Close	

Fig. 4 Define material properties

Fig. 5 Material data

By the same method as above, input material properties for hangers, deck (main girders) and pylons using Table 1.

Table 1 Element material properties

[unit: tonf, m]

lab	Because the self	ត្
	weight of Deck is	,
Cla	directly entered as	
	nodal loads by the	I
	user, Weight Density	
Modul	is assigned 0.	I

Classification	Cable	Hanger	Deck	Pylon
Туре	User Defined	User Defined	User Defined	User Defined
Modulus of Elasticity	2.0 x 10 ⁷	1.4 x 10 ⁷	2.1 x 10 ⁷	2.1 x 10 ⁷
Poisson's Ratio	0.3	0.3	0.3	0.3
Weight Density	8.267	7.85	0.00	7.85

Define Section Properties

Input the section properties using Fig. 6 and Table 2 as follows:



Section

Value>Section ID (1); Name (Cable) Size>D (0.23); Stiffness>Area (0.04178) ↓

Table 2 Section properties [unit: m]					[unit: m]
Classification	Cable	Hanger	Deck	Pylon	Pylon-trans
Area	0.04178	0.00209	0.5395	0.16906	0.1046
kх	0	0	0.4399	0.1540	0.1540
lyy	0	0	0.1316	0.1450	0.1080
lzz	0	0	3.2667	0.1143	0.0913

Note that D=0.23 is used for graphical representation only, and the numerical properties in Section Properties (ie, A=0.04178) are used for analysis. They do not have to necessarily correspond. After entering the Size and clicking on Calc. Section Properties produces the numerical properties, which can be subsequently changed.





Fig. 6 Input section properties (cable)



Input section properties for other elements using Fig. 7 and 8.

Fig. 7 Input section properties for Hanger & Deck (main girder)



Fig. 8 Input section properties for Pylon & Pylon-trans beam

Initial Equilibrium State Analysis

In the completed state analysis of the suspension bridge, the deflections due to selfweight have already occurred, and the structure has come to an equilibrium state. In this initial equilibrium state, the cable coordinates and tension forces are not simply assumed by the designer, but rather they are automatically determined by using equilibrium equations within the program.

Using the **Suspension Bridge Wizard** function, the coordinates of the cables and the initial tension forces within the cables and hangers and the forces in the pylons can be calculated automatically. The initial equilibrium state is determined by inputting the basic dimensions of cable sag, hanger spacing and the self-weight applied to each hanger. The cable and hanger tension forces determined by the Suspension Bridge Wizard are automatically converted into increased geometric stiffness using the **Initial Force for Geometric Stiffness** function within the program.



Fig. 9 2-dimensional basic shape for suspension bridge

To obtain the initial tension forces and basic shape, input appropriate data into *Suspension Bridge Wizard* as per Fig. 10.

Structure / M Suspension Bridge Suspension Bridge Node Coordinates & heights > 3-Dimensional (on) A (0), (0), (20.48) ; A1 (3.6), (0), (20.72); B (128.6), (0), (60.8) ; C (328.6), (0), (27) Height (60.8) Hanger Distance (m) Left (10@12.5) Center (32@12.5) Material> Main Cable (1: Cable) ; Side Cable (1: Cable) Typical Hanger (2: Hanger) ; End Hanger (2: Hanger) Deck (3: Deck) ; Pylon (4: Pylon) Section> Main Cable (1: Cable) ; Side Cable (1: Cable) Typical Hanger (2: Hanger) ; End Hanger (2: Hanger) Deck (3: Deck) ; Pylon (4: Pylon) Deck System Width (11) Shape of Deck (on) ; Left Slope (2.77) ; Arc Length (650) Advanced...(on) Advanced unitweight of deck system Load Type > Point Load (on) Left (9@52.9375) Center (31@52.9375) ↓

Wd (Weight of Deck per unit length): 4.235 tonf/m (assumed) Ld (Longitudinal spacing of hanger): 12.5 m Ignore hanger self-weight

The program automatically calculates the self weight of the cables. Only the self weight of the Deck needs to be entered. As explained earlier, the geometric shape of the suspension bridge, especially the cable coordinates cannot be arbitrarily determined by the designer. Rather they will be determined by the catenary equation satisfying the equilibrium condition within the program. Using the Suspension Bridge Wizard function, the geometric shape and initial tension forces can be calculated. As shown in Fig. 10, all coordinates of the suspension bridge, including the coordinates of the cables can be determined automatically by entering the coordinates of the pylons, sag (B-C), slope of deck, hanger spacing and self weight applied to the hangers.



Fig. 10 Suspension Bridge Wizard Input Window

Fig. 11 is the 3D shape generated by the *Suspension Bridge Wizard* function. The main cables and hangers are generated as cable elements, and the deck and pylons are generated as beam elements.



Fig. 11 Initial equilibrium state analysis using Suspension Bridge Wizard

Divide pylon elements to create pylon transverse beams

Align nodes 258 & 260 in line with node 215 and align nodes 262 & 264 in line with node 247.

Node/Element / Translate... Select Nodes 258, 260, 262, 264 Mode > Move (on) Translation > Equal Distance (on); dx, dy, dz : 0, 0, 2.796635 (z coordinate of nodes 258, 260, 262, 264 = 20.72 and z coordinate of nodes 215 & 247 = 23.516635) Number of times: 1 \downarrow

Solution Input the distances to

pylons.

locate the pylon transverse beams from the top of the

To create the pylon transverse beams, divide the pylons as shown in Fig. 12.





Fig. 12 Pylon element division

Create pylon transverse beams

Generate the pylon transverse beams as follows:

Zoom (Window Magnify the left pylon as Fig. 13)
Node/Elements/ Create...
Element Type>General beam/Tabered beam
Material>4: Pylon ; Section>5: Pylon-trans
Intersect>Node (on) ; Elem (on)
Nodal Connectivity (260, 258) ; (269, 267) ; (268, 266) ^(*) , J



Fig. 13 Generate pylon transverse beams (left pylon)

Generate the pylon transverse beams for the right pylon.

🖾 Zoom Fit

Zoom Window (Magnify the right pylon as Fig. 14) Node/Element / Create Elements Element Type>General beam/Tabered beam Material>4: Pylon ; Section>5: Pylon-trans Intersect>Node (on) ; Elem (on) Nodal Connectivity (264,262) ; (273,271) ; (272,270)



Fig. 14 Generate pylon transverse beams (right pylon)

Remove pylon transverse beams

Remove the very top pylon transverse beams generated by the Wizard.

Node/Element/ ★ Delete Delete... ★ Select Identity-Elements (257,262) Type>Selection (on) ↓



Fig. 15 Remove pylon transverse beams

Input Boundary Conditions

Input boundary conditions for the pylons, cable anchors and the ends of the side spans.

Cable anchors: fix (Nodes: 1, 103, 53, 155)

Pylon base: fix (Nodes: 259, 261, 263, 265)

(Fixed supports are automatically generated and entered upon execution of Wizard.) Ends of side spans: hinge with rotational restraints (Nodes: 205, 257)



Rotational restraint about the bridge axis is provided at the bearings.



Fig. 16 Input Boundary Condition

In this model, the boundary condition for the deck at the pylons is roller, which is separated as shown in Fig. 17. Assign the boundary condition for the deck at the pylons as a roller condition using the **Beam End Release** function.

Zoom Fit ; Zoom Window (Magnify the left pylon part as shown in Fig
17)
Boundary / Beam End Release
Boundary Group Name> Default
Options>Add/Replace
Select Single (Elements: 212)
General Types and Partial Fixity
My (i-Node) (on); Fx (j-Node) (on); My (j-Node) (on) ↓
Select Single (Elements: 213)
General Types and Partial Fixity
Fx (i-Node) (on) ; My (i-Node) (on) ; My (j-Node) (on) ↓



Fig. 17 Input connection condition for the deck at the left pylon

Similarly, assign the boundary condition for the deck at the right pylon.

🔍 Zoom Fit	
🔍 Zoom Window	(Magnify the right pylon part as shown in Fig. 18)
Boundary / Beam En Release	Beam End Release
Boundary Gr	oupName> Default
Options>Add	d/Replace
🟋 Select Si	i ngle (Elements: 244)
General Type	es and Partial Fixity
My (i-Node)	(on); Fx (j-Node) (on) ; My (j-Node) (on) ; ↓
🔭 Select Sl	ingle (Elements: 245)
General Type	es and Partial Fixity
Fx (i-Node)	(on); My (i-Node) (on) ; My (j-Node) (on) ; ↓



Fig. 18 Input connection condition for the deck at the right pylon

In the case of a suspension bridge with dead anchors for cables in which decks (girders) are initially unconnected with hinges while being hung from the hangers and subsequently connected, the decks are unstressed at the initial equilibrium state. In such hinge construction, the Beam End Release function is used to release moments in the decks prior to carrying out the initial equilibrium state analysis using Suspension Bridge Analysis Control.

When releasing moment about My, only one element at a node is released to avoid instability as shown in Fig. 19.



Fig. 19 Pin connection of decks

As shown in Fig, 20, j-end of the decks is **Beam End Released** in the part ①, and iend of the decks is **Beam End Released** in the part ②.



Fig. 20 Pin connection of decks (construction stages)

Define boundary group

```
Group tab
```

Group>BoundaryGroup>New...

Name (Pin Connection)

The decks in the parts (1) and (2) in Fig. 21 are Beam End Released at i-end about M_{V} .

<complex-block>

Fig. 21 Definition of pin connections of decks

The decks in the parts (1) and (2) in Fig. 22 are Beam End Released at j-end about M_{y} .



Fig. 22 Definition of pin connections of decks

Define Structure Groups

In order to carry out the analysis for cable initial shape for the total structural system, which contains the pylons and decks, using Suspension Bridge Analysis Control, we need to define Structure Groups for Sag Points, whose coordinates are unchanged, and Nodes, which need to be updated.

Group>Structure Group>New Name (Nodes to be updated)	
Name (Nodes to be updated)	
Name (Sag Points)	



Fig. 23 Define Structure Groups

In order to execute Suspension Bridge Analysis Control, we define Structure Groups for the nodes joining the cables and hangers and the nodes corresponding to Sag Points of cables at the center span.

Group > Structure Group

Select Identity-Nodes
 (2to10, 12to42, 44to52, 104to112, 114to144, 146to154)
 Nodes to be updated (Drag & Drop)

Select Identity-Nodes (27, 129) Sag Points (Drag & Drop)



Fig. 24 Define Structure Groups

Input loadings

The **Static Load Case**, *Self Weight*, is automatically generated and entered upon execution of Wizard. Define a Load Group for Self Weight and modify the Load Group of Self Weight already created.





Fig 25. Entry of self weight excluding the decks

Since the Weight Density of the decks is 0, the self weight of the decks cannot be considered by the Self Weight function. Because the weight of the decks was entered 0, we specify the self weight of the decks. $^{\Theta}$

 W_d (Weight of Deck per unit length) : 4.235 tonf/m (assumed)

Ld (Longitudinal spacing of hanger): 12.5 m

Ignore hanger self-weight

Self weight of the decks acting on the hangers

Deck : Wd/2 x Ld =4.235 / 2 x 12.5 = 26.469 tonf





Fig. 26 Self weight of decks

Suspension Bridge Analysis Control

Suspension Bridge Analysis Control executes accurate initial equilibrium state analysis for the total structural system, which reflects modified pylons and decks, based on the cable coordinates generated from Suspension Bridge Wizard, unstressed length and horizontal tensions.



Fig. 27 Suspension Bridge Analysis Control

Upon execution of Suspension Bridge Analysis Control, Initial Forces (Large Displacement) are calculated, which are used to represent the initial equilibrium state in large displacement analysis and construction stage large displacement analysis. Initial Forces (Large Displacement) includes Initial Forces for Geometric Stiffness and Equilibrium Element Nodal Force. Initial Forces (Small Displacement) are calculated, which are used to represent initial equilibrium state in linear analysis. Initial Forces (Small Displacement) includes Initial Element Forces. The calculated values can be checked in tables.

Load / Load Tables / Initial Forces for Geometric Stiffness J Load / Static Loads / Initial Forces / Large Displacement / Initial Forces J Load, Static Loads , Initial Forces Initial Forces / Large Displacement / Initial Forces J Load, Initial Element Forces I

Initial Forces (Large Displacement)

Initial Forces for Geometric Stiffness

This is used to represent initial equilibrium state in construction stage large displacement analysis and large displacement analysis. The program internally generates external forces, which are in equilibrium with the entered member forces as well as the initial forces. Once the initial forces are considered for formulating geometric stiffness, the data is ignored in linear analyses such as completed state analysis.

Equilibrium Element Nodal Force (used in construction stage analysis)

Equilibrium Element Nodal Forces are used specifically for backward construction stage large displacement analysis. Without loads, which are in equilibrium with these nodal forces, the nodal forces cause deformation. The nodal forces are ignored in large displacement analysis having no construction stages.

The values of Initial Forces calculated by Suspension Bridge Analysis Control can be readily checked in tables by right-clicking in Works Tree.

Initial Forces (Small Displacement)

Initial Element Forces

Initial element forces are considered in formulating geometric stiffness in completed state linear analysis. This data is ignored if large displacement analysis is carried out.



Fig. 28 Initial Forces Tables

Remove Nonlinear Analysis Control Data and Suspension Bridge Analysis Data

Linearized finite displacement analysis is sufficient for the completed state analysis, so it is carried out as such. However, because initial equilibrium state analysis is carried out by nonlinear analysis when Suspension Bridge Wizard is executed, Nonlinear Analysis Control Data is generated. We now need to remove Nonlinear Analysis Control Data to perform linear analysis. Also, once we obtain member forces to formulate geometric stiffness through Suspension Bridge Analysis Control, we can then remove Suspension Bridge Analysis Data to perform completed state analysis.

•••
-

Nonlinear Analysis Control	
Nonlinear Type	
Geometry Nonlinear	Material Nonlinear
_Iteration Method	
Newton-Raphson C Arc-Length	C Displacement-Control
Number of Load Steps :	1
Maximum Number of Iterations/Load Step :	30 🔺
Convergence Criteria	
Energy Norm :	0.001
☑ Displacement Norm :	0.001
Force Norm :	0.001
Load Case Specific Nonlinear Analysis Control D	Data
Load Case	Add
	Modify/Show
	Delete
Remove Nonlinear Analysis Control Data	OK Cancel

Fig. 29 Remove Nonlinear Analysis Control Data

Suspension Bridge Analysis Control			
Control Parameters			
Number of Iterations		10 .	
Convergence Toleran	ce	1e-005	
Analysis Method			
 Inital Force 	C Optim	ization Approach	
Node Group to be Upda	ted	Nodes to be updat 💌	
Sag Point Group		Sag 💌	
Constant Horizontal	Force of C	able	
Main Cable Group	No	des to be updated 💌	
Horizontal Force	0	tonf	
Define Girder Z-Displacement Condition			
∟Load Cases to be Con	sidered —		
Load Case Se	lf Weight	▼ …	
Scale Factor 1			
Load Case !	Scale	Add	
Self Weight	1	Modify	
		Delete	
Remove Suspension Bridge Analysis Data			
	OK	Cancel	

Fig. 30 Remove Suspension Bridge Analysis Data

Remove and Modify Beam End Release Conditions for Deck

After initial equilibrium state analysis, completed state analysis is performed with the decks being connected. As such, we now remove the Beam End Release conditions for the decks.

Tree Menu>**Works tab** Boundaries>Beam End Release>Type 1 : **Delete** ↓ Boundaries>Beam End Release>Type 4 : **Delete** ↓



Fig. 31 Delete Beam End Release

The pylons and decks are connected to carry out the completed state analysis. So we remove the Beam End Release conditions for the decks.

Tree Menu>Works tab Boundaries>Beam End Release>Type 1 : Properties J My (i-Node) (off) J Boundaries>Beam End Release>Type 2 : Properties J My (j-Node) (off) J



Fig. 32 Modify Beam End Release

Input center span stay

At the center part of the center span, we model the center stay, which will equalize the movement of the girders and the main cable in the axis of the bridge. The structural type of the center stay is normally a center diagonal stay type or a linking type. In this tutorial, we will model the center stay that connects the girders and cables using the Elastic Link function.

 ☑ Zoom Fit ;
 ☑ Zoom Window

 Node Number (on)
 Boundary /

 Boundary /
 Elastic Link

 Elastic Link
 Elastic Link

 Boundary Group Name>Default
 Options>Add

 Link Type>General Type>SDz (1e11)
 2Nodes (27, 78)

 Copy Elastic Link>Distance>Axis>y (on)>Distances (11) ↓



Fig. 33 Connection of Deck (main girders) and cables
Input Load Cases and Static Loads

In order to examine the behavior of the suspension bridge at the stage of the completed state, we assume static vehicle test loading and input the static loads as shown in Fig. 35. We first generate static load cases as shown in Fig. 34.

Load/ Static Loads / Static Load Cases Name (LC1) ; Type > User Defined Description (Static Load Test) J Name (LC2) ; Type >User Defined Description (Static Load Test) J Name (LC3) ; Type > User Defined Description (Static Load Test) J

Nam	e :	LC3	•		Add
cas		All Load Cas	e (harro)		Polate
i ypi	2 :	User Define	I LOAD (USER)	<u> </u>	Delete
Desi	cription :	Static Load	lest		
	No	Name	Туре	Descrip	tion
	1	Self Weight	Dead Load (D)	Self Weight	
	2	LC1	User Defined Load (USER)	Static Load Test	
	3	LC2	User Defined Load (USER)	Static Load Test	
	4	LC3	User Defined Load (USER)	Static Load Test	
*					

Fig. 34 Define Static Load Cases



Assume the vehicle weight as 46 tonf, and apply the load at three different locations as separate load cases.

Fig. 35 Static Load cases

```
Apply static loads to the main girders.

Load / Static Loads / Nodal Loads Nodal Loads

Select Identity-Nodes (231)

Load Case Name>LC1

Load Group Name>Default ; Options>Add

Nodal Loads>FZ (-46) J

Select Identity-Nodes (223)

Load Case Name>LC2 ;

Nodal Loads>FZ (-46) J

Select Identity-Nodes (210)

Load Case Name>LC3 ;

Nodal Loads>FZ (-46) J
```



Completed State and Construction Stage Analyses of a Suspension Bridge

Fig. 36 Input static load (LC1)

Perform Structural Analysis (Completed State Analysis)

We will perform structural analysis as the modeling for the completed state analysis is now completed.



Review Results of Completed State Analysis

Static Analysis Results

Review displacements and member forces for the three static load cases.

Review deformed shape

🗎 Front View	
Result/ F Deformations / F Deformed Shape	
Load Cases / Combinations > ST: LC1	
Components>DXYZ	
Type of Display> Undeformed (on); Legend (on) ↓	



Review deformed shapes for load cases 2 & 3 using the same procedure.

Result / F Deformations > / F Deformed Shape... Load Cases / Combinations > ST: LC2 Components>DXYZ Type of Display>Undeformed (on) ; Legend (on) , J Load Cases / Combinations > ST: LC3 Components>DXYZ Type of Display>Undeformed (on) ; Legend (on) , J Review displacements in a tabular format at the loading locations.

Results / Results Results Tables

Result Tables / **Displacements**

Records Activation Dialog>Node or Element>**210 223 231** Loadcase/Combination> **LC1**, **LC2**, **LC3** (on) →

1				_		_			
	Node	Load	DX (m)	DY (m)	DZ (m)	RX (Ired1)	RY (Iredi)	RZ (fredt)	
	210	1.01	0.001226	0.000000	0.061272	0.000000	0.000032	0.000000	
-	223	LC1	-0.001220	0.0000000	-0.031367	0.000000	0.002232	0.000000	
	231	LC1	0.000000	0.000000	-0.314879	0.000000	0.000000	0.000000	
	210	LC2	-0.000905	0.000000	0.045233	0.000000	0.000024	0.000000	
	223	LC2	-0.050267	0.000000	-0.371234	0.000000	0.000110	0.000000	
4	231	LC2	-0.051756	0.000000	-0.031236	0.000000	-0.003462	0.000000	
-1	210	LC3	0.004880	0.000000	-0.243808	0.000000	-0.000092	0.000000	
-	223	103	-0.015600	0.000000	0.045897	0.000000	-0.000328	0.000000	
	231	163	-0.015706	0.000000	0.002533	0.000000	-0.000000	0.000000	
						Re Re	cords Activ	ation Dialo	
						Node	or Element		Loadcase/Combination
						A	I No	n In	e Pre Self Weight(ST)
						Node	Ŧ	210 220	✓ .CL(S) ✓.C2(S) ✓.C2(S)
						Sele	ct Type		A44
							lent rype		
						TRL	SS M		Delete
						PLA	NE STRESS		
						PLA	TE NE CTD ATM		Replace
						AXI	SYMMETRIC		Intersect
						100	-		
► 15	UISPla	cements	1						

Fig. 38 Displacement table

Review bending moments

Review bending moments in the deck.

Results / Forces / Beam Diagrams... Load Cases/Combinations>ST:LC1 ; Components>My DisplayOptions>5 Points ; Line Fill Type of Display>Contour (on) ; Legend (on) J



Fig. 39 Bending moment diagram for Deck (LC1)

Review axial forces

Review axial forces in the main cables.

Result / Forces * / Truss Forces Load Cases/Combinations>ST:LC1 Force Filter>All Type of Display>Contour (on) ; Legend (on) ,J



Fig. 40 Max tension forces in the cables (LC1)

Review the cable axial forces in tabular format.

Results / Result Tables / Truss / Force Records Activation Dialog>Node or Element> Select Type>Material>1: Cable Loadcase/Combination> LC1, LC2, LC3 (on)



Fig. 41 Table of tension forces in the main cables

* The above output of axial forces shows the additional axial force in the cables. At the initial equilibrium state, tension forces due to the self weight have already occurred. Therefore, the total member forces in the cables and hangers then become the summation of the above axial forces and the *Initial Force for Geometric Stiffness* introduced during preprocessing.

The following procedure will generate the total axial forces, which include both the initial forces and additional forces determined previously.

Load / 🛱 Initial Forces 🎽 /Small Displacement/ 🖂 Initial Forces Control Data Add Initial Force to Element Force (on)

Load Case > LC1 ↓

Initial Force Contr	ol Data	X
Add Initial Fo	orce to Element Force	
Load Case :	LC1	•
Initial Force	Combination —	
Load Case :	LC1	▼
Scale Factor :	1	
Load Case	e Scale	Add
		Modify
		Delete
Check to Refle	ct Initial Axial Forces in	to Geometric
	ОК	Cancel

Fig. 42. Initial Force Control Data



_

Review the cable axial forces in the tabular format.

Results / Result Tables / Truss / Force	
Records Activation Dialog>Node or Element>	
Select Type>Material>1: Cable	Replace
Loadcase/Combination> LC1 (on) ↓	

Burn Loss Final Final 2 Loss Final Final 3 Loss Final Final 4 Loss Final Final 3 Loss Final Final 4 Loss Final Final 5 Loss Final Final 6 Loss Final Final Final 7 Loss Final Final Final 6 Loss Final Final Final 7 Loss Fi	1	1			
Image: Construction Image: Construction Image: Construction 3 C C 1957-108 1957-124 4 C C 1957-108 1957-124 5 C C 1957-108 1957-124 6 C C 1957-108 1957-124 7 C C 1957-108 1957-124 8 C C 1957-128 1957-124 9 C C 1957-126 1957-124 9 C C 1957-126 1957-124 9 C C 1957-126 1957-124 10 C C 1957-126 1957-126 10 C C 1957-126 1957-126 10 C C 1957-126 1957-126 10 C C C 1957-126 1957-126	Ele	m Load	Force-I	Force-J	
IC 10472974 10453974 IC 10472974 10490295 IC 10472974 10490295 IC 104902974 10490295 IC 104902974 10490295 IC 104902974 10490297 IC 1049029719 10490297 IC 1049029719 10490297 IC 1049029719 10490297 IC 1049029719 10497497 IC 10490297199 10497497 IC 104974989 104974989 IC 10497499			(tont)	(tont)	
2 C(2) 164-1748 055-7587 3 C(2) 1578-253 056-055 4 C(2) 1578-253 056-055 7 C(2) 158-057 056-055 8 C(2) 158-057 056-055 9 C(2) 158-057 056-055 9 C(2) 158-057 056-055 9 C(2) 158-057 0578-057 10 C(2) 059-057 0578-057 11 C(2) 059-0578-057 0578-057 15 C(2) 158-050 1578-057 16 C(2) 158-050 1578-057 16 C(2) 158-050 1557-056 16 C(2) 158-050 1558-050 16 C(2) 158-050 158-050 16 C(2) 158-050 158-050 16 C(2) 158-050 158-050 17 C(2) 158-050 158-050 18 C(2) 158-050 158-050 18 C(2) 158-050 <th></th> <th>1 LC1</th> <th>1547.2974</th> <th>1548.5237</th> <th></th>		1 LC1	1547.2974	1548.5237	
3) C(2) 195,216 195,216 4) C(2) 195,206 195,217 4) C(2) 195,206 195,217 4) C(2) 195,206 195,206 4) C(2) 195,206 195,206 4) C(2) 195,206 195,207 195,206 4) C(2) 195,206 195,206 195,206 4) C(2) 195,206 195,206 195,206 5) C(2) 195,206 195,206 195,206 6) C(2) 195,206 195,206 195,206 7) C(2) 195,206 195,206 195,206 7) C(2) 195,206 195,206 195,206 7) C(2) 195,206 195,206 195,207 7) C(2) 195,207 196,207		2 LC1	1554.7148	1555.7587	
4 (C1 179 169 179 169 177 160 179 160		3 LC1	1562.3184	1563.4528	
s C(1) 179:3209 100:300.000 0 C(2) 150:4001 100:000.000 0 C(2) 150:4001 100:000.0000 0 C(2) 150:2000 100:000 100:000 1 C(2) 150:2000 100:000 100:000 100:000 1 C(2) 150:2000 100:000		4 LC1	1570.4989	1571.7241	
6 C(1) 198 8110 199 0255 7 C(2) 199 0255 199 0255 8 C(2) 199 0255 199 0255 9 C(2) 199 0257 193 0256 16 C(2) 199 0205 199 0257 17 C(2) 199 0205 199 0257 18 C(2) 199 0207 199 0257 19 C(2) 199 0207 199 0257 19 C(2) 199 0207 199 0207 19 C(2) 199 0207 199 0207 10 C(2) 199 0207 1007 0207 10 C(2)<		5 LC1	1579.2639	1580.5801	
7 IC1 198.9574 000.0064 8 IC1 190.000 100 100 9 IC1 190.000 100 100 10 IC1 190.000 100 100 100 10 IC1 190.000 100 100 100 100 10 IC1 190.000 100		6 LC1	1588.6180	1590.0255	
0 1C1 1000 1007 100 1007 100 1007 100 1007 100 1007 100 1007 100 1007 100 1007 100 1007 100 1007 100 1007 100 1007 100 1007 100 1007 100 1007 100 1007 100 1007 100 1007		7 LC1	1598.5674	1600.0664	
0 1C1 102.2006 021.970 10 1C2 102.000 021.970 11 1C2 102.000 021.970 12 1C2 103.000 1030.000 1030.000 13 1C2 1050.000 1030.000 1030.000 1030.000 14 1C2 1050.000 1030.000 1030.000 1000.000 1000.000 16 1C2 1030.000 1030.000 1030.000 1000.000		8 LC1	1609.1223	1610.7130	
10 10 <td< th=""><th></th><th>9 LC1</th><th>1620.2960</th><th>1621.9787</th><th></th></td<>		9 LC1	1620.2960	1621.9787	
11 11 <td< th=""><th></th><th>10 LC1</th><th>1632.0719</th><th>1633.8468</th><th>Records Activation Dialog</th></td<>		10 LC1	1632.0719	1633.8468	Records Activation Dialog
12 [C1 158.1000 979.8774 13 [C1 158.1000 979.8774 14 [C1 158.1000 979.8774 15 [C1 158.1000 979.8774 16 [C1 158.1000 979.8774 16 [C1 158.1000 979.8774 16 [C1 158.200 158.900 17 [C1 158.400 158.900 18 [C1 158.200 158.900 18 [C1 158.200 158.900 18 [C1 158.200 158.200 18 [C1 158.200 158.200 18 [C1 158.200 158.200 18 [C1 158.200 158.200 18 [C2 158.200 158.200 19 [C2 158.200 158.2		11 LC1	1590.9002	1589.4844	
13 121 121 127 126 197 126 12		12 LC1	1581.2005	1579.8774	Note or Element Loadrase Combination
14 LC1 158.026114 Al Bose Prev Set Work(ST) 15 LC1 158.026114 Mile Prev Set Work(ST) 16 LC1 158.026114 Mile Prev Set Work(ST) 16 LC1 158.026114 Mile Prev Set Work(ST) 17 LC1 158.0261 Status Mile Mile Prev Set Work(ST) 18 LC1 158.0261 Status Mile Mile Prev Set City		13 LC1	1572.1508	1570.9201	
19 IC (1) 1954 022 0554 002 0554 002 0554 002 10 IC (2) 1554 026 0554 002 055 002 056 002 0		14 LC1	1563.7599	1562.6214	All None Inverse Prev Self Weight(ST)
16 10:10:1 10:48.4897 40:79:400 40:10:10:10:10:10:10:10:10:10:10:10:10:10		15 LC1	1556.0121	1554.9655	
17 IC1 152.4040 551.505 16 IC1 153.2078 153.0078 18 IC1 153.2078 153.0078 21 IC1 1551.2078 153.0078 22 IC1 1551.2078 153.0078 23 IC1 1551.2078 153.0078 24 IC1 1554.207 1554.207 25 IC1 1554.207 1552.208 26 IC1 1554.207 1552.208 26 IC1 1554.207 1552.208 26 IC1 1554.207 1552.208 27 IC1 1554.207 1552.208 28 IC1 1554.207 1552.208 29 IC1 1554.207 1552.208 20 IC1 1554.208 1552.208 21 IC1		16 LC1	1548.8957	1547.9408	Element v 1052 10200153
16 1(c) 158.8329 838.7090 Peech.1(#************************************		17 LC1	1542,4040	1541.5406	Columb Trans
19 1(c) 153/1276 553.5857 Matrix Add 21 1(c) 153/1276 553.5857 Delte Add 21 1(c) 154.2461 153.2767 Add Delte 21 1(c) 154.2461 154.0276 S14.027 Add Delte 21 1(c) 154.2461 154.0261 S14.027 IS1.2561 Delte 23 1(c) 154.2461 154.1276 IS1.1276 Delte Intersect 23 1(c) 154.2462 154.1276 IS1.1276 IS1.1276 IS1.1276 24 1(c) 154.2462 154.1277 IS1.1264 Intersect Intersect 25 1(c) 154.2661 154.2661 154.2661 Is1.2760 Is1.2646 36 1(c) 154.2661 154.2661 Is1.2760 Is1.2646 Is1.2760 36 1(c) 154.2661 Is1.2646 Is1.2770 Is1.2646 Is1.2770 37 1(c) 154.2661 Is1.2770 Is1.2646 Is1.2770 Is1.2646 <td< th=""><th></th><th>18 LC1</th><th>1536.5329</th><th>1535,7608</th><th>Seecury</th></td<>		18 LC1	1536.5329	1535,7608	Seecury
10 1C1 15584420 15584520 1558520 15585520 15585520 15585520 15585520 15585520 15585520 15585520 15585520 <th></th> <th>19 LC1</th> <th>1531,2796</th> <th>1530.5987</th> <th>Material Add</th>		19 LC1	1531,2796	1530.5987	Material Add
1 1/1 1/1 1/1 1/2 1/1 1/2 1/1 1/2 1/1 1/2		20 LC1	1526.6420	1526.0522	1 : Cable
22 1.C1 193.8000 318.8001 23 1.C4 193.8000 193.8000 24 1.C1 193.4000 193.8000 26 1.C1 193.8000 193.8000 26 1.C1 193.8000 193.8000 26 1.C1 193.8000 193.8000 27 1.C1 193.8000 193.8000 26 1.C1 193.8000 193.8000 27 1.C1 193.8000 193.2000 28 1.C1 193.8000 193.2000 29 1.C1 193.8000 193.2000 20 1.C1 193.8000 193.2000 29 1.C1 193.8000 193.2000 20 1.C1 193.8000 193.2000 20 1.C1 193.8000 193.2000 20 1.C1 193.4000 193.2000 20 1.C1 193.4000 193.2000 20 1.C1 193.4000 193.2000 20 1.C1 193.4000 193.2000 21 1.		21 LC1	1522.6184	1522.1198	2 : Hanger Delete
23 LC1 155 155 155 33 LC1 155 155 155 34 LC1 155 155 155 35 LC1 155 155 155 36 LC1 155 155 155 37 LC1 155 155 155 38 LC1 155 155 155 39 LC1 155 155 155 31 LC1 155 155 155 33 LC1 155 155 155 34 LC1 155 155 155 35 LC1 155 155 155 36 LC1 155 155 155 37 LC1 155 155 155 36 LC1 155 155 155 37 LC1 155 155 155 38 LC1 155 155 155 36 LC1 155 155 155 37 LC1 155 155 155 38 LC1 155 155 155 37 LC1 155 <td< th=""><th></th><th>22 LC1</th><th>1519,2080</th><th>1518,8001</th><th>3 : Deck</th></td<>		22 LC1	1519,2080	1518,8001	3 : Deck
Av LC1 1514.2020 </th <th>_</th> <th>23 LC1</th> <th>1516.4130</th> <th>1516.0958</th> <th>4 : Pyton Replace</th>	_	23 LC1	1516.4130	1516.0958	4 : Pyton Replace
36 IC1 192,2105 192,2105 192,2105 192,2005		24 LC1	1514,2420	1514.0155	
36 10:1 <		25 LC1	1512,7187	1512 5829	Drids Sect
27 [C1 1911/873 9111/874 28 [C4 1954/855 1952/874 30 [C4 1954/855 1952/874 31 [C4 1958/866 1958/867 33 [C4 1958/867 1958/867 34 [C4 1958/867 1958/867 35 [C4 1958/867 1958/867 36 [C4 1958/867 1958/867 37 [C6 1958/867 1958/867 38 [C1 1954/867 1958/867 39 [C1 1954/867 1958/877 30 [C1 1954/867 1958/877 31 [C1 1954/867 1958/877 32 [C2 1958/877 1958/877		26 LC1	1511.9244	1511.8730	
38 LC1 193.2803 193.7907 OK Canod 38 LC1 193.4935 194.2405 194.2405 194.2405 38 LC1 193.4935 194.2405 194.2405 194.2405 38 LC1 193.4935 194.2405 194.2405 194.2405 39 LC1 193.4935 194.2405 194.2405 194.2405 31 LC1 193.4935 194.2405 194.2405 194.2405 31 LC1 193.4936 194.4305 194.2405 194.2405 32 LC1 193.4936 194.4307 194.2416 194.4307 32 LC1 193.4946 194.4307 194.2416 194.2416 194.2416 33 LC1 193.4947 197.1406 197.1406 197.1406 197.1406 197.1406 34 LC1 197.4946 197.1406 197.1406 197.1406 197.1406 197.1406 35 LC1 197.1407 197.1406 197.1		27 LC1	1511.8730	1511.9244	
39 IC1 154.0155 154.2050 31 IC2 155.0061 154.2050 32 IC3 155.0061 154.2050 33 IC2 1552.2016 152.2016 34 IC3 1553.5007 1533.2705 35 IC2 1553.5007 1534.2000 36 IC3 1554.2016 1542.4010 36 IC3 1554.2016 1554.2016 37 IC4 1554.2016 1554.2016 38 IC4 1574.2016 1564.0017 39 IC4 1574.2016 1574.2016 38 IC4 1574.2016 1574.2016		28 LC1	1512.5829	1512.7187	OK Cover
30 C(-1) 151.6001 516.401 516.		29 LC1	1514.0155	1514,2420	
31 LC1 151.8000 151.2001 32 LC1 151.2016 152.2016 33 LC1 152.016 152.016 34 LC1 153.000 153.1700 35 LC1 154.500 153.1700 36 LC1 154.500 155.4007 37 LC1 154.500 155.0700 39 LC1 154.4007 156.9017 39 LC1 154.4007 150.9700 40 LC1 157.1700 1 41 LC1 157.2700 1		30 LC1	1516.0958	1516.4130	
32 [C:1 152:116 152:11		31 LC1	1518.8001	1519.2080	
3) L(c) 158.8022 158.84620 3) L(c) 158.9097 151.2766 3) L(c) 158.9097 151.2766 3) L(c) 158.4080 158.4080 10 L(c) 158.4080 158.4087 3) L(c) 158.4080 158.907 3) L(c) 158.4080 158.907 3) L(c) 158.4080 158.907 3) L(c) 157.4000 157.909 46 L(c) 157.4000 157.1000		32 LC1	1522.1196	1522.6184	
34 (C1 153,896) 15312706 35 (C1 155,706) 155,8520 36 (C1 1541-560 1558,520) 37 (C1 1541-560 1542-660 38 (C1 1554-660 1560-021 38 (C1 1554-660 1560-021 39 (C1 1552,001 155,150) 30 (C1 1554,660 157,150) 31 (C1 1552,001 157,150) 4 (33 LC1	1526.0522	1526.6420	
36 ICC1 1536,7000 1536,7000 37 ICC1 1547,1400 1547,1400 30 ICC1 1547,1400 1548,0400 30 ICC1 1548,0400 1559,0500,110 30 ICC1 1558,0251 1640,0570 30 ICC1 1558,0251 1640,0570 30 ICC1 1558,0251 1640,0570 30 ICC1 1558,0251 1559,0500 31 ICC1 1558,0251 1559,0500 32 Tonss Force / 4		34 LC1	1530.5987	1531.2796	
36 IC1 1541-506 1552-650 37 IC3 1547-506 1548-8957 38 IC1 1554-8857 1556-9757 39 IC1 1572-5079 4 10 IC3 1572-15789 1542-15789 10 IC3 1572-15789 4		35 LC1	1535.7608	1536.5329	
37 IC1 14/37 Holis 14/48 Holis 14/37 Holi		36 LC1	1541.5408	1542.4040	
36 [C1 1554:485 1556:01] 39 [C1 1554:485 1556:01] 40 [C2 1574:00] 1972:1590 40 [C2 1574:00] 1972:1590 41 [C2 1574:00] 1972:1590 4		37 LC1	1547.9408	1548.8957	
39 [CC1 1558.2744 (69.37596) 40 [CC1 1578.061 (57.168) 7) Transa Force / 4 (CC1 (57.168)		38 LC1	1554.9655	1556.0121	
40 LC1 1578 500 1572 1508 ≥ N Trass Force / 4		39 LC1	1562.6214	1563.7599	
2) Truss force /		40 LC1	1570.9201	1572.1508	
	D \ Tr	uss Force			•
And	Model	Man Po	cult-France	Forcel/	F

Fig. 43 Sum of initial forces and additional forces in cable

Modeling for Construction Stage Analysis

A suspension bridge is relatively unstable during construction compared with the completed state. Therefore, geometric nonlinear analysis (large displacement analysis) must be performed instead of linearized finite displacement analysis or P-Delta analysis. Moreover, construction sequence analysis is warranted to reflect the forces and displacements of previous stages in the subsequent stages.

In this chapter, we will perform a backward construction stage analysis for the construction of a suspension bridge starting from the completed state analysis model that was created earlier. The backward analysis sequence used in this tutorial is shown in Fig. 44.



Fig. 44 Sequence of backward construction stage analysis

Assign Working Environment

To generate a construction stage analysis model using the final stage analysis model, we first save the completed state analysis model data under a different file name.



Save As (Suspension Bridge Construction.mcb)

To generate a construction stage analysis model, the following should be added to the completed state analysis model.

Modeling

Define construction stages

Define elements, boundary conditions and loadings pertaining to each construction stage.

Define Structure groups

Group elements that are added / deleted at each construction stage.

Define Boundary groups

Group boundary conditions that are added / deleted at each construction stage.

Define Load groups

Group loads that are added / deleted at each construction stage.

Analysis

- > Nonlinear Analysis (geometric nonlinear analysis)
- Construction Stage Analysis

Define Construction Stage Names

Define construction stages for backward construction stage analysis. First, define all the names to be used for the construction stages by using the Construction Stage dialog box. Then, define Structure Groups, Boundary Groups and Load Groups pertaining to each construction stage, and assign each group to a corresponding construction stage.

In this tutorial, there are eight construction stages defined including the completed state as shown in Fig. 45.





Fig. 45 Define the construction stage names using the Construction Stage dialog box

Define the names of the construction stages using the same prefix and different suffix numbers.

When generating output for each construction stage, the output for each construction stage is saved and produced.

Assign Structure Groups

Assign elements, which are added or deleted in each construction stage, to the Structure Groups. First, create the name of each Structure Group, and then assign the corresponding elements.

```
Tree Menu>Group tab
```

Group>Structure Group> New... (right-click on Structure Group) Name (S_G) ; Suffix (0, 2to7) ما



Fig. 46 Define Structure Groups

Assign elements, which are added/deleted in each construction stage to a corresponding Structure Group. At the completed state - final stage (CS0) and the stage in which the deck is pin connected (CS1), the corresponding elements are identical, and only the boundary condition is changed. Therefore, we will define the construction stage as Structure Group S_G0 .

Tree Menu>Group tab

🕭 S	Select	AI
-----	--------	----

Group>Structure Group>S_G0 (Drag & Drop)



Fig. 47 Define Structure Group (S_G0)

Define the deck and hangers, which are deleted in the backward construction stage CS2, as Structure Group S_G2.

- When selecting elements, all elements intersected by the selection window can be selected if the selection window is created from right to left.
- To define the structure group precisely, inactivate the previously defined element group to prevent it from being selected in another element group.

Tree Menu>**Group tab**Select Window (Elements: Fig. 48 ①, ②)

Group>Structure Group>S_G2 (Drag & Drop)

S G2>Inactivate



Fig. 48 Define Structure Group (S_G2)

Define the deck and hangers, which are deleted in the backward construction stage CS3, as Structure Group S_G3.





Fig. 49 Define Structure Group (S_G3)

Define the deck and hangers, which are deleted in the backward construction stage CS4, as Structure Group S_G4.



Fig. 50 Define Structure Group (S_G4)

Define the deck and hangers, which are deleted in the backward construction stage CS5, as Structure Group S_G5.

Tree Menu>**Group tab** Select Window (Elements: Fig. 51 ①, ②) Group>Structure Group>**S_G5** (*Drag & Drop*) S_G5>Inactivate



Fig. 51 Define Structure Group (S_G5)

Define the deck and hangers, which are deleted in the backward construction stage CS6, as Structure Group S_G6.

Tree Menu>**Group tab** Select Window (Elements: Fig. 52 ①, ②) Group>Structure Group>S_G6 (*Drag & Drop*) S_G6>Inactivate



Fig. 52 Define Structure Group (S_G6)

Define the deck and hangers, which are deleted in the backward construction stage CS7, as Structure Group S_G7.



Fig. 53 Define Structure Group (S_G7)

Assign Boundary Groups

Assign boundary conditions for each construction stage to Boundary Groups. First, we generate the name of each Boundary Group, and assign boundary conditions for each construction stage to a corresponding Boundary Group already generated.

Activate All

Group tab>BoundaryGroup>**New… (right-click on Boundary Group)** Name (**B_G**) ↓ Name (**Stay**) ↓ Name > (**Pin Connection**) already exists ↓



Fig. 54 Create Boundary Group Names

We now group boundary conditions for the pylons, cable anchorages and deck ends. Using the Drag & Drop function, we change the boundary condition group name (Default) already defined to B_G .

 Image: Select All

 Tree Menu>Group tab

 Group>BoundaryGroup>B_G (Drag & Drop)

 Select Boundary Type



Fig. 55 Changing boundary condition group name

Grouping center span stay

Assign the center span stay, modeled by Elastic Link, as a Boundary Group named "Stay".

Tree Menu>**Group tab** Select All Boundary Group>**Stay** (*Drag & Drop*) Select BoundaryType>**Elastic Link** (on) ما



Fig. 56 Grouping center span stay

Pin connections at deck

We assign hinge conditions to the deck in the same way as we did for the completed state analysis. We specify **Beam End Release** about moment My at the i-end of the deck in the parts ① & ② of Fig. 57 and assign them to the boundary group, "Pin Connection", at the same time.





Fig 57 Define Pin Connections at deck

We specify **Beam End Release** about moment My at the j-end of the deck in the parts 0 & 2 of Fig. 58 and assign them to the boundary group, "Pin Connection", at the same time.





Fig 58 Define Pin Connections at deck

Define Construction Stage Loads and Load Groups

We will remove the loads used in the completed state analysis since they are not used in construction stage analysis. Since the loads in construction stage analysis were not defined in the completed state analysis, we will define the loads for the construction stages and define the Load Groups simultaneously.



Fig. 59 Define construction stage static load

We will use the Load Group (L_G) already defined for the completed state analysis. When elements are eliminated in construction stages, the self weights of those elements are also eliminated. In construction stage analysis, the Equilibrium Element Nodal Forces calculated in the process of the completed state analysis are applied to the member internal forces. Therefore, the construction stage process is modeled such that only the deck and hanger elements are eliminated in each stage and their internal forces are redistributed 100% to the contiguous elements.

Define Construction Stages

Assign the previously defined structure groups, boundarygroups and load groups to the corresponding stages. Table 4 shows the elements, boundary conditions and load groups that are activated or deactivated in each construction stage.

Charge	Structu	ure Group	Boundary Grou	Load Group		
Stage	Activ ate	Deactiv ate	Activate	Deactiv ate	Activ ate	Deactiv ate
CS0	S_G0		B_G, Stay		L_G	
CS1			Pin Connection	Stay		
CS2		S_G2				
CS3		S_G3				
CS4		S_G4				
CS5		S_G5				
CS6		S_G6				
CS7		S_G7				

Table 4 Element, boundary condition and load group for each construction stage

CS0: Completed state (final stage)

CS1: just before the decks (main girders) are rigidly connected (pin connection stage) CS2 \sim CS7: construction stages in which the decks (main girders) and hangers are erected (refer to Fig. 43) Define the construction stage CS0 (Completed state stage)



Fig. 60 Define construction stage CS0

Define Construction Stage CS1(Pin Connection stage).

Load / Construction St	age / Define Co	onstruction	Stage	
Name>651	<u>IM</u> oully/310W			
Save Resu	ılt> Stage (on)			
Boundary>	Group List> Pin Con	nection; Act	ivation> ^{Add}	
Boundarv>	Group List> Stav : D)eactivation>	Add 🗸	
	_ ,			
Compose Constr	uction Stage			—
Stage			Additional Steps	1 1
Stage :	CS1	<u>_</u>	Day: 0 Add	Delete
Name :	CS1		(Example: 1, 3, 7, 14) Modify	Clear
Duration :	0	t day(s)	Auto Generation	Day
Save Result				
	▼ Stage		Step Number : 0	
			Generate Steps	
	Current Stage Information			
Element Bour	dary Lad			
Group List		Activation	Deactivation	
B_G		Support / Spring Positio	on	
		○ Original	formed	
		Group List	Group List	
		hame Posit	tion Name	
		Pin Connection Dero	stay	

Fig. 61 Define Construction Stage CS1

Add Modify Delete

Add Delete

OK Cancel Apply

Define Construction Stage CS2.

ត្

is

When



Fig. 62 Define Construction Stage CS2

For efficiency, we will use the *MCT Command Shell* even though the remaining construction stages (CS3-CS7) can be defined using the same procedure as above. Repetitive input such as defining the construction stages can be easily input using the *MCTCommand Shell*. The techniques used to input the construction stage information by the *MCTCommand Shell* is as follows:



Fig. 63 MCT Command Shell

As shown in Fig. 62, the construction stage information comprises eight lines of commands. Each command is defined below.

NAME: construction stage name, number of days of construction for the
stage, flag for saving output
STEP: time Step
AELEM: activated structure group and its initial age
DELEM: deactivated structure group and its internal force redistribution factor
for its section forces
ABNDR: activated boundary group and location
DBNDR: deactivated boundary group
ALOAD: activated load group and time step
DLOAD: deactivated load group and time step

MCT Command Shell

MCT Command Shell

MCT Command enData: "STAGE Insert Command Insert Data Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Delete Data

Del

Modify the information for the construction stages CS3-CS7 using the **MCT Command Shell** as shown in Fig. 64.

Fig. 64 MCT Command Shell

After input has been completed in the MCT Command Shell, we then simply click the Run button to compose the construction stages with the following messages generated.

Warning in line 27 : *STAGE 데이터가 변경되었습니다.	
Warning in line 30 : *STAGE 데이터가 변경되었습니다.	_
Warning in line 33 : *STAGE 데이터가 변경되었습니다.	
Execute HCT command - 0 error(s), 8 warning(s)	

Confirm whether the construction stages have been correctly defined or not on the Model View.

💻 Display
Boundary tab
Support (on) ; Beam End Release Symbol (on)
Rigid Link (on); Elastic Link (on)
Load tab
Load Case>All (on); Nodal Load (on) 니

Stage>CS3

Control of New 201 Control of New 20		Decomposed Decomposed Services Se
Itree Menu Task Pane For Help, press F1 Command Message fi	Analyse Message / Frame-119 Ur: 222.35, 11, 36.55124 (6: 222.35, 11, 36.55124	4 torf en e 순숙화/rove 1 1만/ 2 것

Fig. 65 Check the defined construction stage (CS3) shown on Model view

G Construction stages can be easily viewed on the Model View by simply selecting the construction stages using the direction key on the keyboard, if the Stage Toolbar is activated.

Input Construction Stage Analysis Data

Select the Last Stage and analysis type for the construction stage analysis. Select the large displacement analysis option, as the effect of large displacements cannot be ignored when calculating forces for construction of a suspension bridge. Nonlinear construction stage analysis is carried out while reflecting the Equilibrium Element Nodal Forces calculated in the completed state analysis.

Stage> Base	
Analysis /	Construction Stage Analysis Control
Const	truction tage
Final Stage> L	Last Stage (on)
Analysis Optio	on> Include Nonlinear Analysis (on)
> Ind	lependent Stage (on)
	>Include Equilibrium Element Nodal Forces (on)
Convergence	Criteria> Displacement Norm (on) ↓

Equilibrium Element Nodal Force calculated in the completed state analysis is reflected in the internal member forces.

C Last Stage C Other Stage CS0	Number of Load Steps :
Restart Construction Stater Analysis Select Stages for Restart. Analysis Option Conduction Analysis Ondependent Stage Condependent Stage Conductions Construction	Convergence Citeria
Indude equilarium Bernert Noar Protes Adude 2-Deta Analysis Control Indude Time Dependent Effect Time Dependent Effect Time Dependent Effect Load Case i Self Weight Multiple Time Dependent Time Dependent Effect	C Al C Group Nodes to be updated C Lad-of-Ph-Force Control C Conder Stress Decrease at Lead Length Zone by post-tension C Linear Internoteino C Conder Stress Centrol
Load Type for C.S. (Erection Load) : Dead Load of Wearing Surfaces and	Beam Section Property Changes Constant
	Frame Output Calculate Concurrent Forces of Frame Calculate Output of Each Part of Composite Section

Fig. 66 Construction Stage Analysis Control Data dialog box

Perform Structural Analysis (Construction Stage Analysis)

Now that we have completed the construction stage analysis model, we will perform structural analysis.



Review Construction Stage Analysis Results

Review the change in the deformed shapes and section forces for each construction stage.

Review Deformed Shape

We will examine the global behavior of the structure by checking the deformed shape at each construction stage. The deformed shape at the construction stage CS7, which represents the completed pylons and main cables, is shown in Fig. 66.

If the basic Deformation Scale Factor is too large, adjust the factor to view the deformed shape.

Review the deformed shapes for different construction stages by changing the construction stages by using the Stage Toolbar. Mouse wheel or up/down keys on the keyboard may be used. Results , fl Deformations > / fl Deformed Shape... Load Cases / Combinations > CS: Summation Components>DXYZ Type of Display>Undeformed (on) ; Legend (on) Deform ---->Deformation Scale Factor (0.2) + ... Stage Toolbar>CS7 +



Fig. 67 Check the deformed shapes for different construction stages
Review the change of the center span sag, which is used as a measure of erection precision during construction at each construction stage, by a graph.

Results / 💹 Stage/Step Graph Stage/Step History Graph
Define Function>Displacement> Add New Function
Displacement>Name (Sag); Node Number (27)
Components> DZ ₊J
Mode > Multi Func.
Step Option > Last Step
X-Axis > Stage/Step
Check Functions To Plot > Sag (on)
Load Cases/Combinations > Summation
Graph Title > Sag



Fig. 68 Changes of the Sag magnitudes through construction stages

Determine a setback

Review the magnitude of a setback for the pylons at the stage when the deck (main girders) and hangers have not been erected.

Results / I Deformations / I Deformed Shape Stage Toolbar>CS7 Load Cases / Combinations >CS: Summation Components>DX Type of Display>Undeformed (on) ; Legend (on) ↓



Fig. 69 Review setback value

Setback value

Suspension bridges are designed to have no bending moments in pylons at the completed state stage by maintaining the applied horizontal forces in equilibrium at the tops of the pylons. However, if the cable is erected with the same center span length of the completed state stage, the resulting horizontal forces at the tops of the pylons are not in an equilibrium condition, and hence, cable slip will likely occur. The tops of the pylons are relocated (a type of horizontal camber) to set the horizontal cable forces balanced left and right. Generally, the tops of the pylons are pulled toward the side spans by wire ropes, and this is called setback.

We will now review the horizontal displacements changing with the construction stages at the top of a pylon by using a graph. As shown in Fig. 69, the horizontal displacement in backward construction stage CS7 becomes the setback value of the pylons.





Fig. 70 Horizontal displacements of a pylon with changing construction stages

Review moments

Review the moments in the deck (main girders) and pylons (towers) for each construction stage. It is the characteristic of an earth-anchored suspension bridge that the deck (main girders) are subject to no moments due to dead loads during the construction stages and at the initial equilibrium state. Whereas, the towers are not subject to moments at the initial equilibrium state with the horizontal forces in equilibrium, but moments are developed during construction as shown in Fig. 70.

Results / 🚰 Forces 🔪 / 🤟 Beam Diagrams
Construction Stage > CS2
Load Cases>Combinations>CS: Summation
Components> My
DisplayOptions>5 Points ; Line Fill
لم (on) ; Legend (on) Type of Display>Contour



Fig. 71 Review of moments at each construction stage

Review axial forces

Review axial forces in the main cables & hangers for each construction stage.

Results / Forces / Image Forces... Construction Stage > CS2 Load Cases / Combinations>CS: Summation Force Filter>All Type of Display>Contour (on) ; Legend (on) +J



Fig. 72 Review of axial forces in the main cables and hangers

Review the change in tension forces in the cable adjoining the top of the right pylon for each construction stage.

Results / 🖳 Stage/Step Graph Stage/Step History Graph

Define Function>Truss Force/Stress> Add New Function Truss Force/Stress >Name (Cable Force) ; Element No (43) Force (on) ; Point>i-Node ↓

Define Function>Beam Force/Stress> Add New Function Beam Force/Stress >Name (Tower Axial Force); Element No (261) Force (on); Point>i-Node; Components>Axial J

Mode > Multi Func. Step Option > Last Step X-Axis > Stage/Step Check Functions To Plot>Cable Force ; Tower Axial Force Graph Title > Cable Force and Tower Axial Force



Fig. 73 Graph showing the change in main cable tension force at each construction stage

Review deformed shape using animation

_

Review the deformed shapes for each construction stage using the Animation function.

View/ Hidden (toggle on)
Results / F Deformations / F Displacement Contour
Components>DXYZ
Type of Display> Contour (on) ; Deform (on)
Legend (on) ; Animate>
Animation Details>Animate Contour (on)
RepeatFull Cycle > (on)
Frames per HalfCycle (5~50)> (8)
Frames per Second (5~50)> (8)
Construction Stage Option>Stage Animation
From> CS0 ; To> CS7 ↓
Record →
Close



Fig. 74 Review of deformed shapes for each construction stage using the Animation function