

Finite Element Modeling of Long-Span Steel Suspension Bridges in Civil Engineering



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Outline

- > Overview of the the Fatih Sultan Mehmet Bridge located in Istanbul, Turkey
- > Finite element modeling
- > Eigenvalue analysis results
- > Earthquake simulations (recent progress)
- > Conclusions

The Fatih Sultan Mehmet Bridge – a.k.a. The Second Bosphorus Bridge

- > Composed of steel towers and steel deck
- > Span length: 1090m
- > 2 x 4 lanes of traffic; commercial truck traffic (in the past) and now only local commuter traffic is allowed
- > Total mass of 34,000 metric tons of steel
- > Opened to service in July 1988 – built by a consortium of Japanese companies including the IHI Corporation and Mitsubishi Heavy Industries

The Fatih Sultan Mehmet Bridge – a.k.a. The Second Bosphorus Bridge

- > Tower height above the road level: 98m
- > Deck level above sea: 66m
- > The 3m-high and 39.40m-wide bridge deck is a hollow steel box section composed of orthotropic stiffened panels
- > Diaphragm wall panels exist in the deck structure approximately at every 4m.

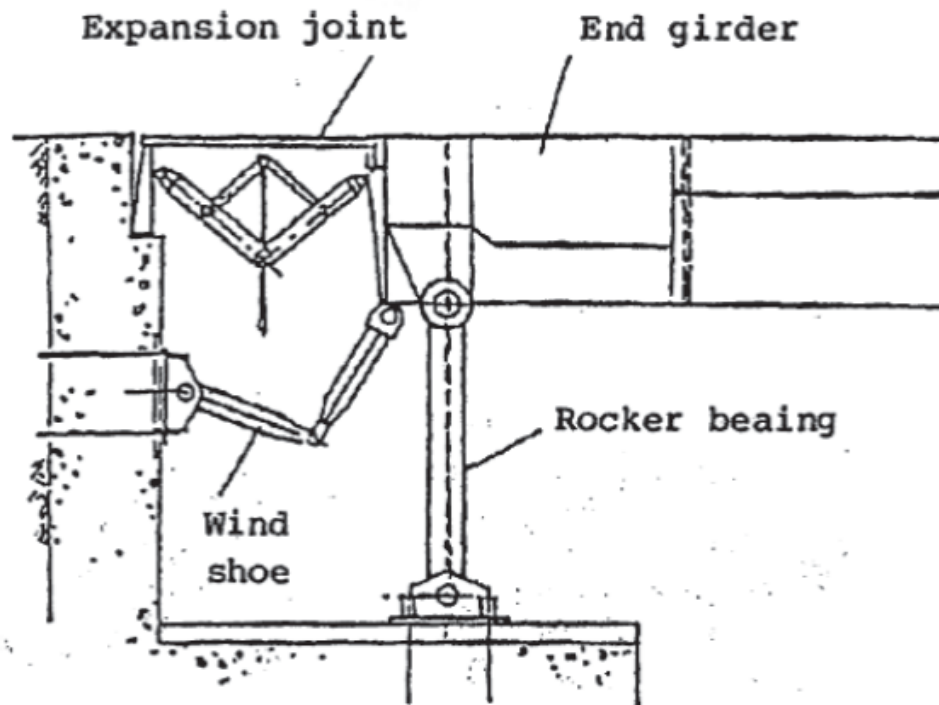
The Fatih Sultan Mehmet Bridge



The Fatih Sultan Mehmet Bridge: Journey Back in Time (1987)



The Fatih Sultan Mehmet Bridge: Articulation; Rocker Bearing and Windshoe



The Fatih Sultan Mehmet Bridge: Articulation; Windshoe



BTITLE

The Fatih Sultan Mehmet Bridge: Articulation; Rocker Bearing



BTITLE

Line/Beam Element Models

> Advantages:

Easy to construct

Fast run-time

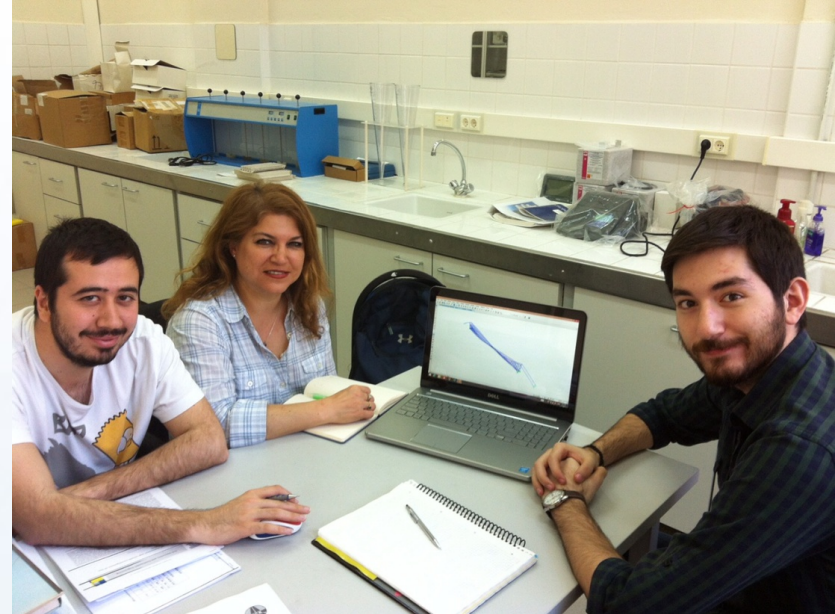
> Disadvantages:

Reasonable accuracy for global behavior

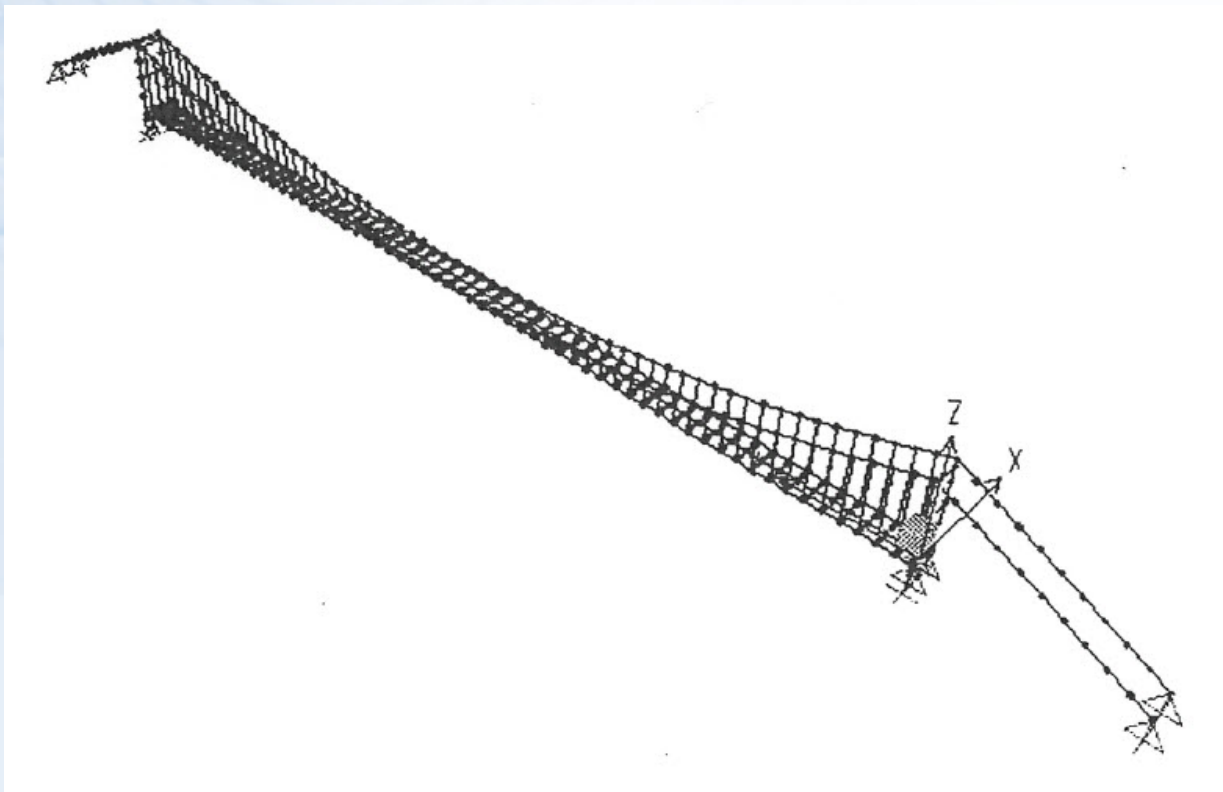
Poor accuracy for higher modes

Poor accuracy particularly for torsional modes

Not suited for modeling non-linear effects such as plastic strain concentration, impact between two entities coming into contact



The Fatih Sultan Mehmet Bridge: Previous Work Done Using a Line Element Model



Shell Element Models

> Advantages:

Better accuracy; no need to fine-tune the model; no fudge factors; no adjustment knobs necessary

Suited for non-linear simulations

Better visualization

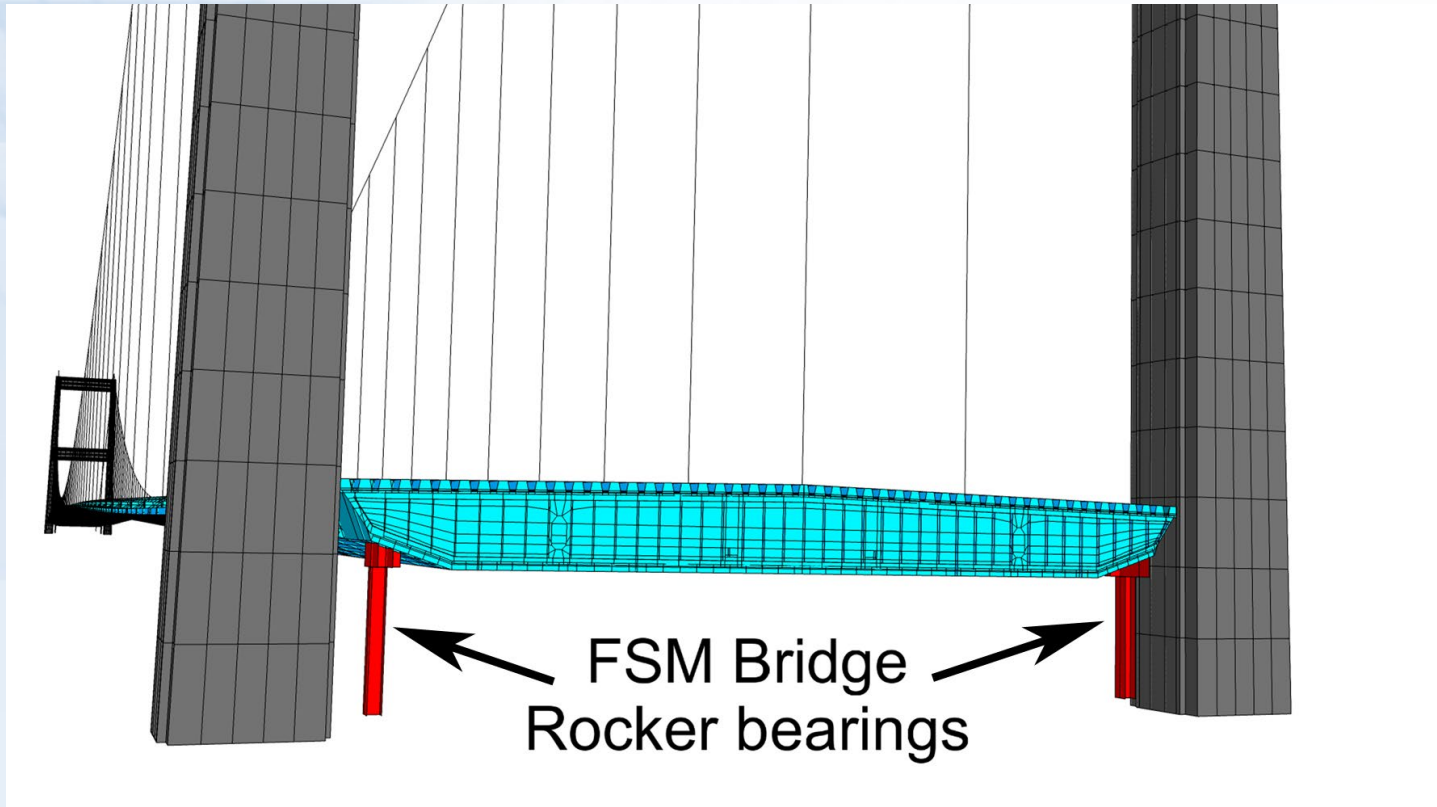
> Disadvantages:

Difficult to construct

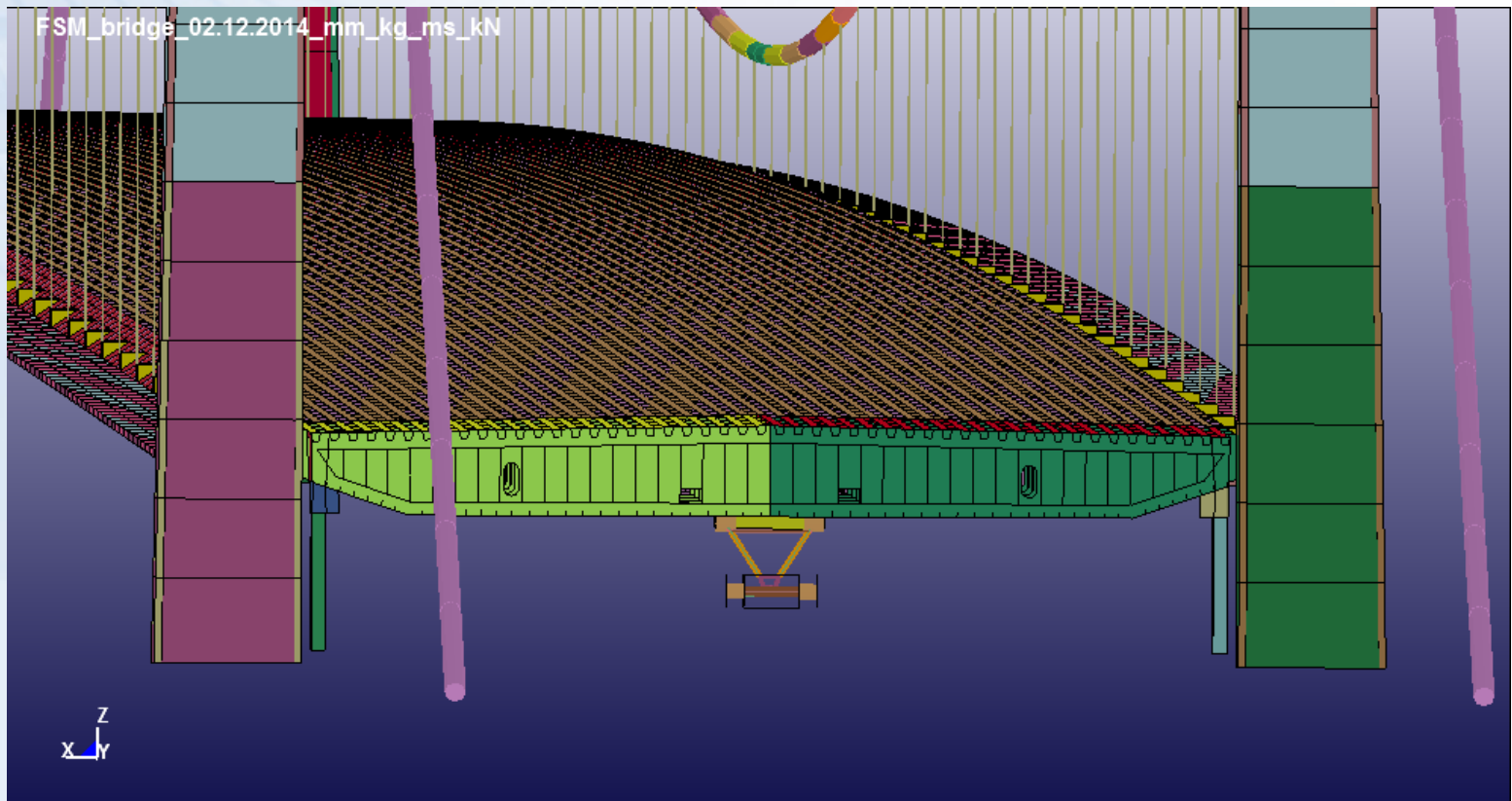
Increased run-time for computations

Requires high performance parallel computing platforms for practical use

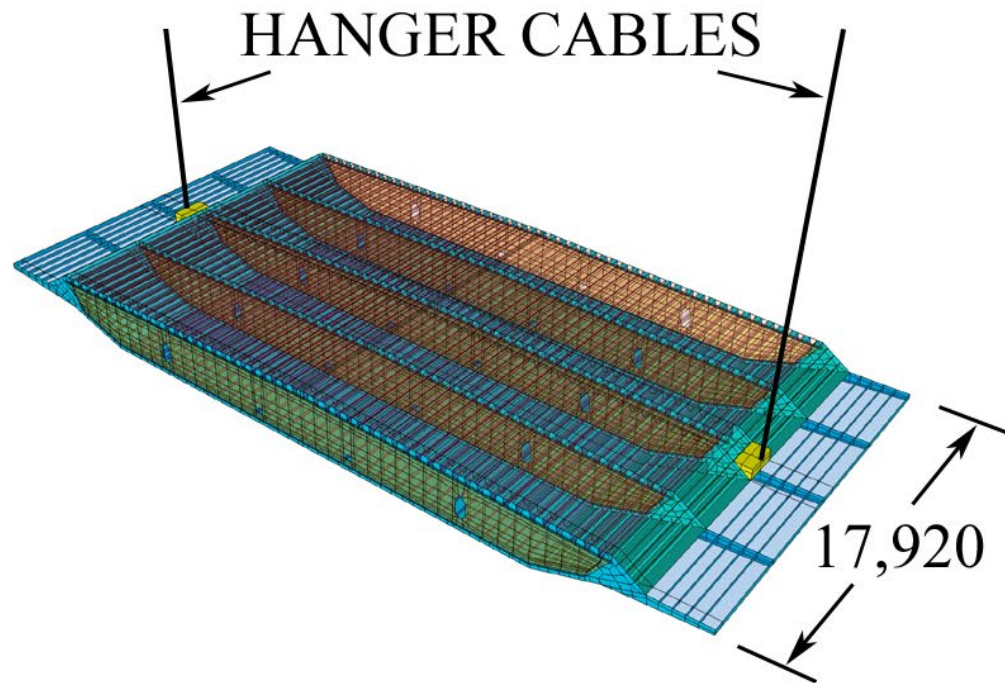
FSM: Shell Element Model (Continued)



FSM: Shell Element Model (Continued)



FSM: Shell Element Model (Continued)



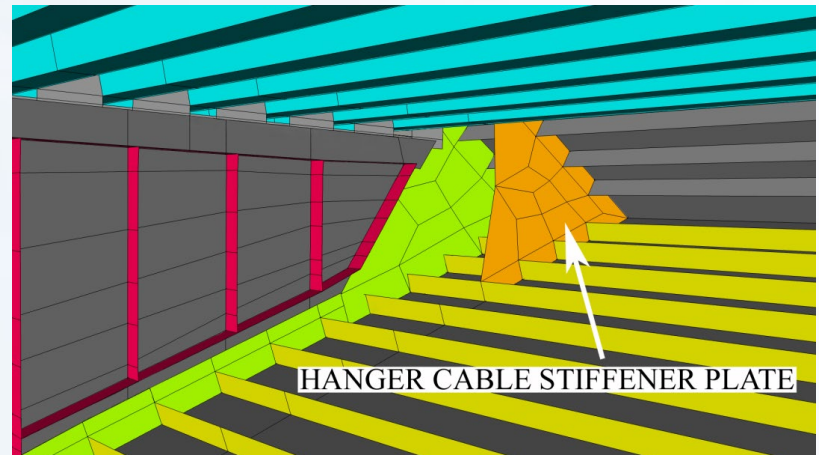
* The span dimension is given in millimeters.

FSM: Shell Element Model (Continued)

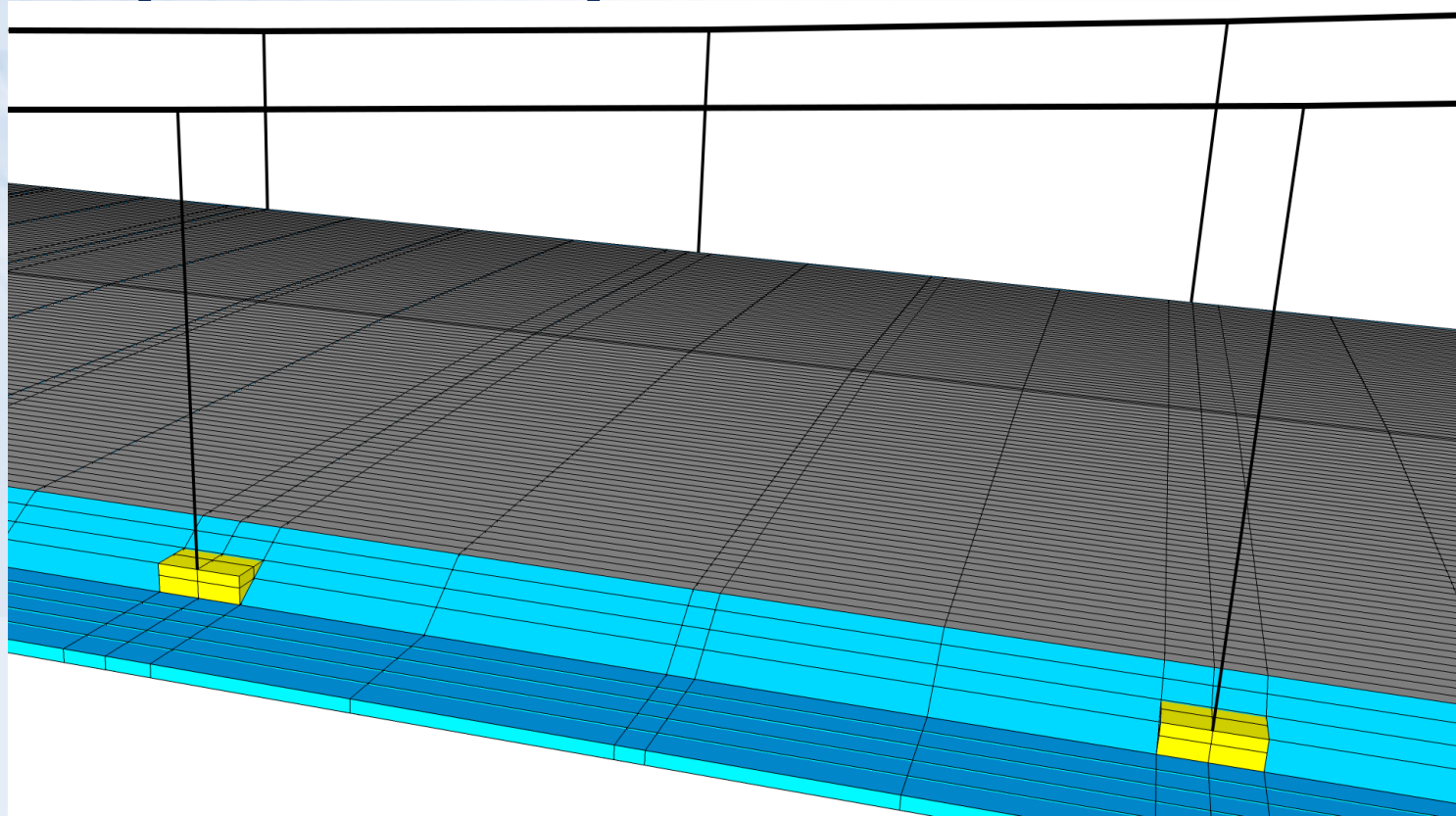


Photo of the
actual structure

LS-Dyna shell model



FSM: Shell Element Model (Continued)



FSM: Implicit Analysis Steps

The computations are done in a two-step scheme, i.e. in a first step the gravity load and cable pre-straining are applied simultaneously; the eigenmodes, modal masses and modal participation factors are calculated in the second step using the full restart capability of LS-DYNA. In this way the static pre-straining is separated from consecutive computations which allows for more flexibility during simulation runs.

FSM: Implicit Analysis Steps

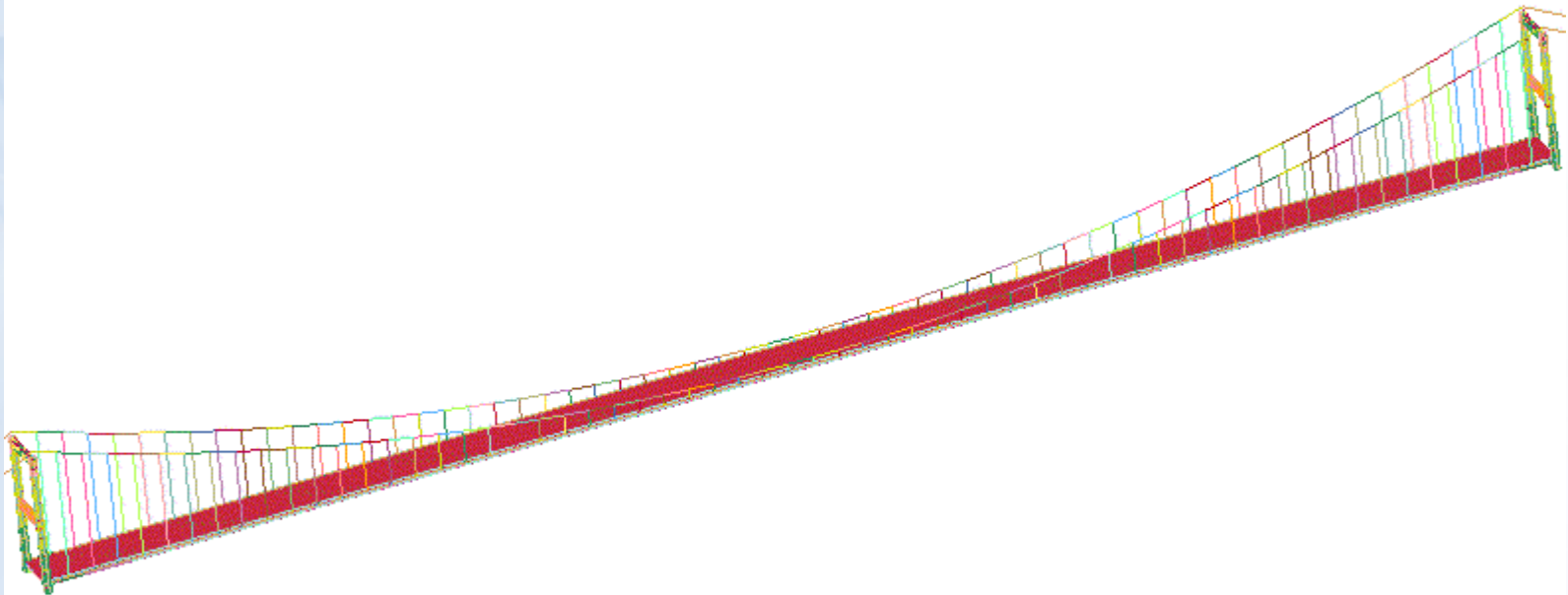
The non-linear static analysis of applying gravity load and cable pre-straining is achieved by means of LS-DYNA's full Newton solver, which is needed here since the default Broyden-Fletcher-Goldfarb-Shannon (BFGS) solver fails to obtain convergence. The gravity load and the pre-straining of the cables are applied in a synchronous way, i.e. both effects cancel each other and no displacements are observed; equilibrium is accomplished after four iterations. For the inherent matrix factorization the double precision direct sparse linear solver from the Boeing Extreme Mathematical Library (BCSLIB-EXT) is applied, which is a robust solver with sufficient numerical stability for such an intricate stiffness matrix where the dimensions vary over a range of several orders of magnitude. Utilizing one 12 core node of the Linux cluster JUDGE at Jülich Supercomputing Centre (JSC) SMP LS-DYNA needs 35 minutes for this non-linear static analysis.

FSM: Implicit Analysis Steps

The solution of the eigenvalue problem is done by means of LS-DYNA's block shift and invert Lanczos eigensolver from BCSLIB-EXT. The computation of the first 40 eigenmodes is achieved by SMP LS-DYNA in 25 minutes using again one node with 12 cores. These first 40 eigenmodes are not sufficient to catch all important contributions to modal masses, i.e. the modal mass is well below 90% of the total physical mass for x-translational, y-translational and z-translational modes. In fact, one has to compute the first 1300 eigenmodes in order to meet the 90% accumulated modal mass demand. This computation takes almost 10 hours using 12 cores. Despite the computational effort, the dominant number of the calculated 1300 eigenmodes are pure cable modes, which are not of importance for the present study, but are inevitably calculated in the eigenvalue analysis.

Eigenvalue Results: Lateral Mode

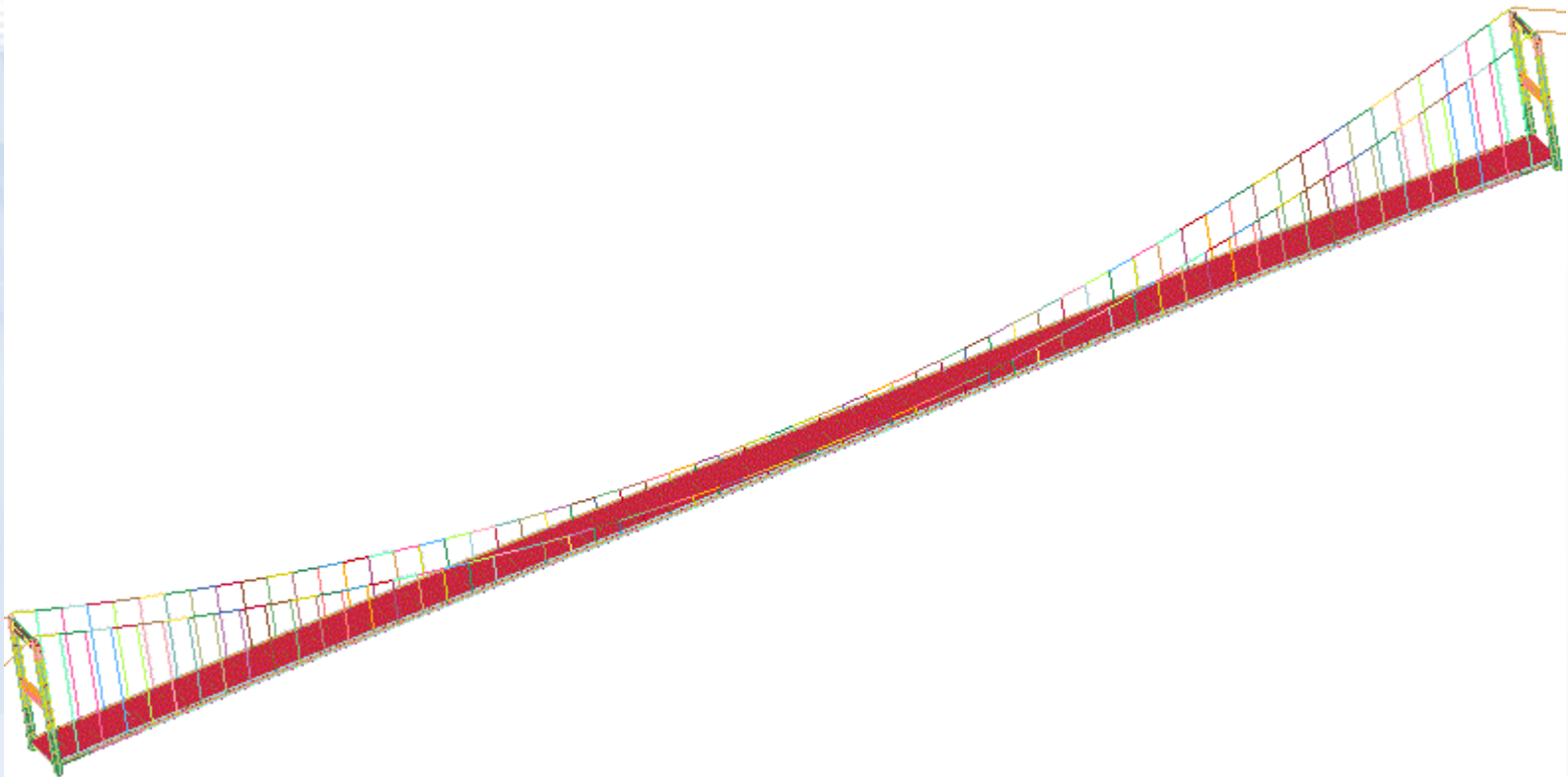
LS-DYNA eigenvalues at time 5.00100E+0
Freq = 7.3982e-005



Eigenvalue Results: Vertical Mode

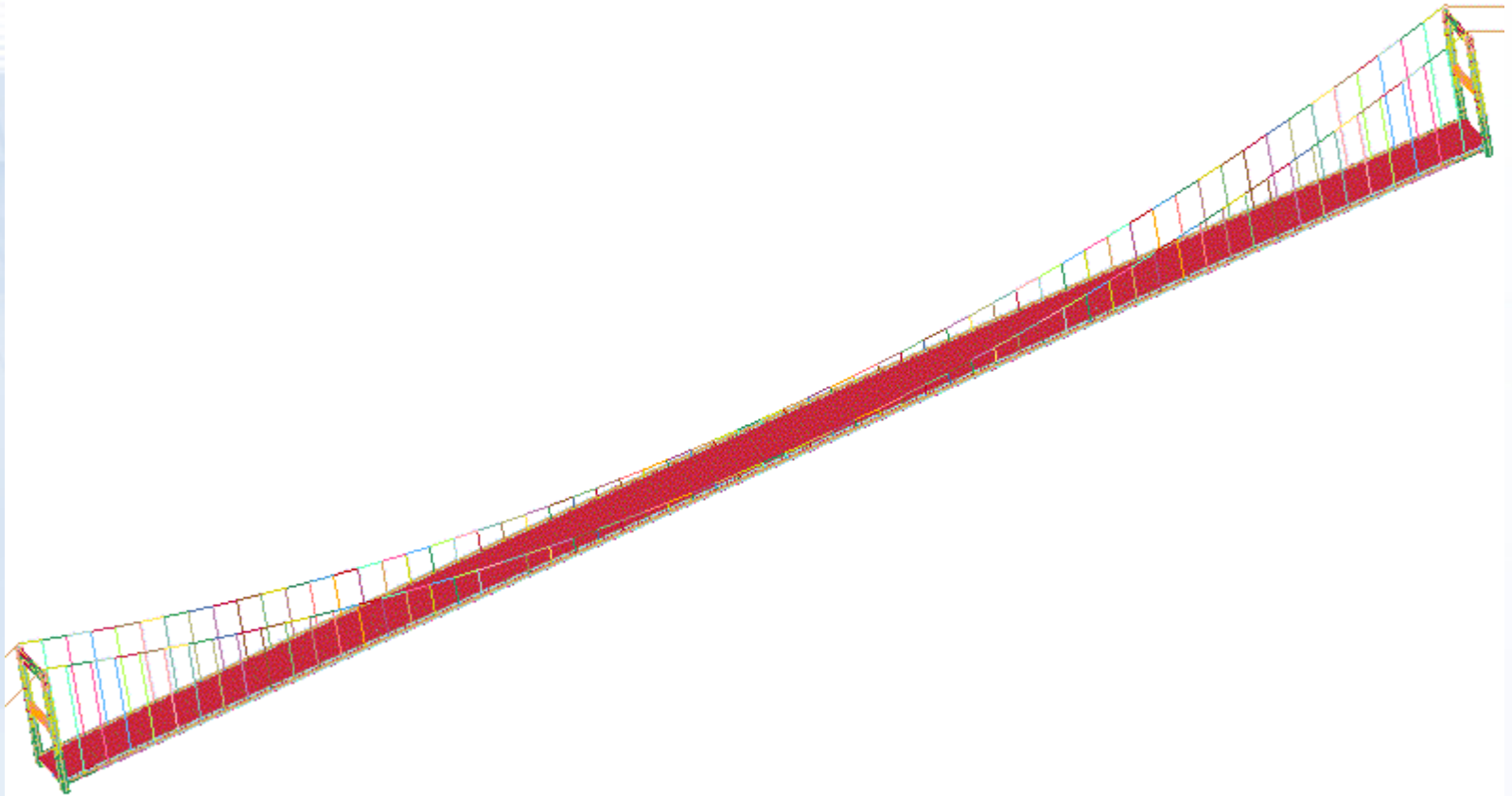
LS-DYNA eigenvalues at time 5.00100E+0

Freq = 0.00015804

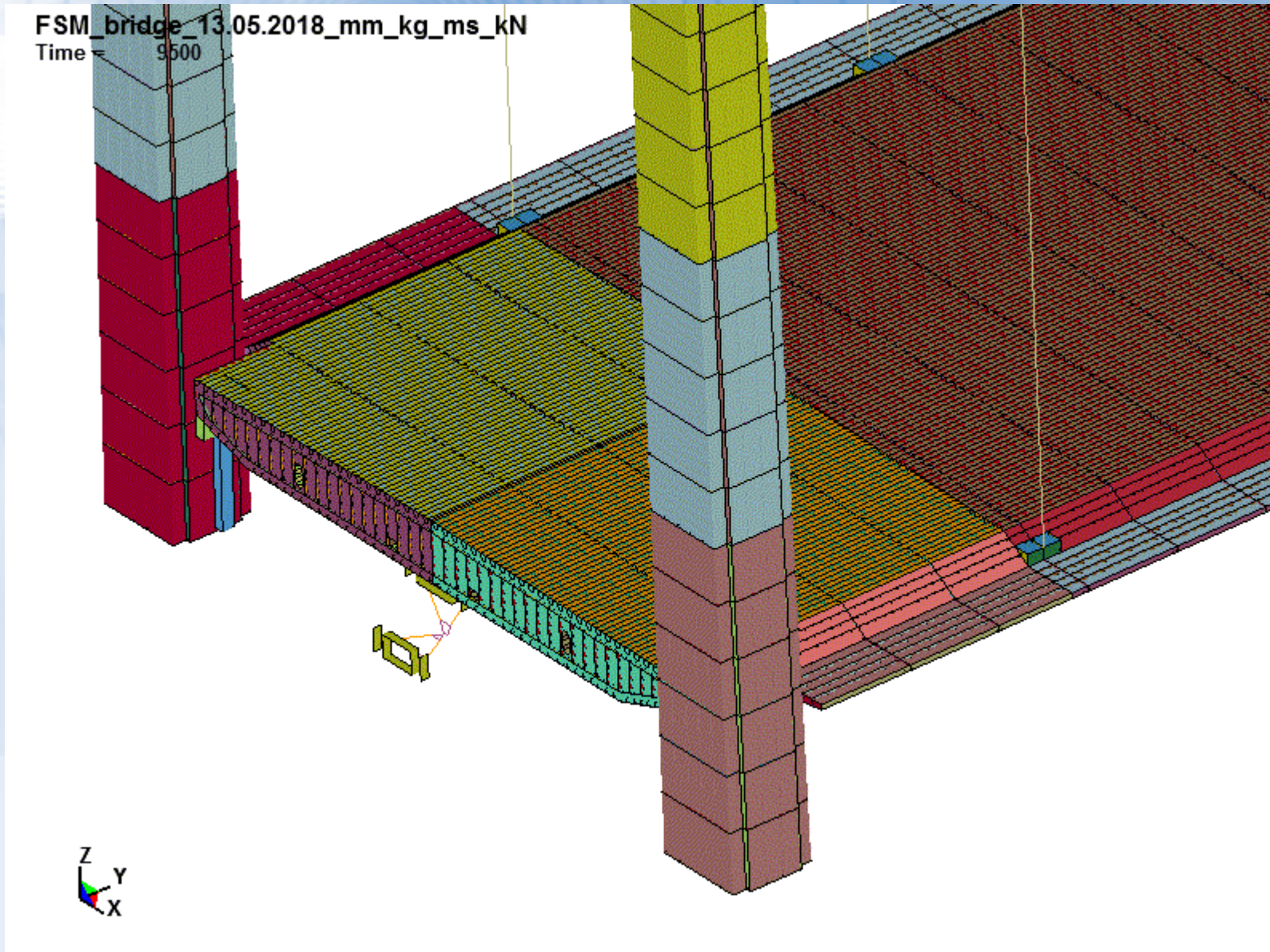


Eigenvalue Results: Torsional Mode

LS-DYNA eigenvalues at time 5.00100E+0
Freq = 0.00029196



Erdbeben Results: Catwalk to Tower Impact



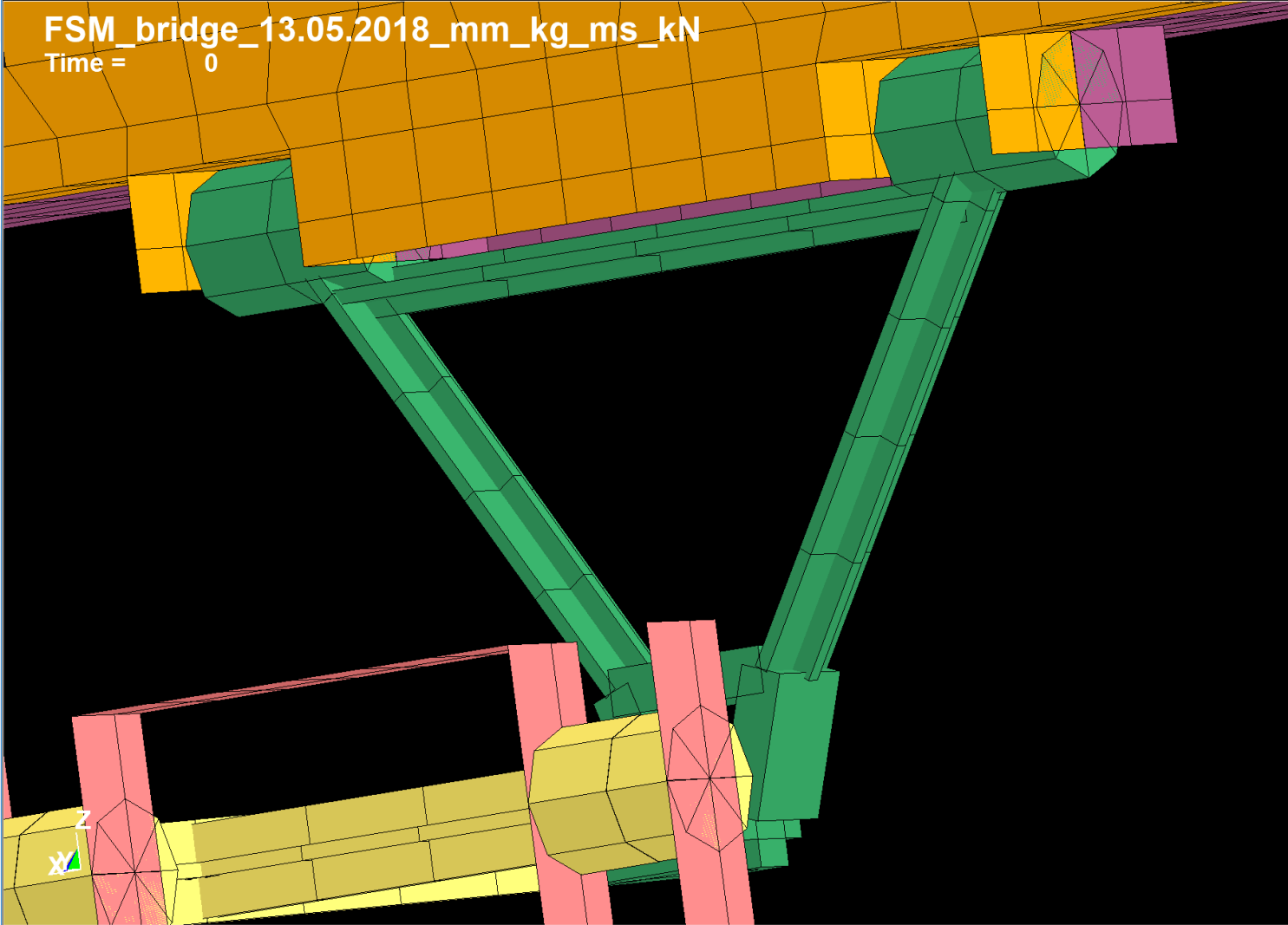
Earthquake/Erdbeben Simulations with Implicit-Explicit Switching

MPP Domain Decomp. Problem Constraints

LS-PrePost(R) V4.3 (Beta) - 24Nov2015(09:00)-64bit N:\4d.fsm.second.paper\d3plot

File Misc. Toggle Background Applications Settings Help

FSM_bridge_13.05.2018_mm_kg_ms_kN
Time = 0



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Find	Ident	ASCII
Fcomp	History	Views
Appear	Color	Model
Group	Blank	SelPar

1 2 3 4 5 6 7 D

Part Selection

- Md1 S 163
- S 164
- Beam S 165
- Shell S 166
- Solid S 167
- S 168
- Tshell S 169
- CNRB S 170
- Mass S 171
- S 172
- Disc S 173
- SBelt S 174
- S 175
- Inerts S 176
- Rsurf S 177
- Sphn S 178
- Fluid/ S 179
- NURB S 180
- DiscS S 181
- S 182
- MSms S 183
- S 184
- Singl S 185
- Area S 186
- Poly S 187
- S 188
- S 189
- Save S 190
- Load S 191
- S 192

Title	Off	Tims	Triad	Bcolr	Unode	Frin	Isos	Lcon
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selectpart on S190/0
selectpart on S191/0
selectpart on B95/0 S191/0
beamprism 1
selectpart on B95/0 S190/0 S191/0
selectpart on B95/0 B96/0 S190/0 S191/0
selectpart on B95/0 B96/0 S190/0 S191/0 S192/0

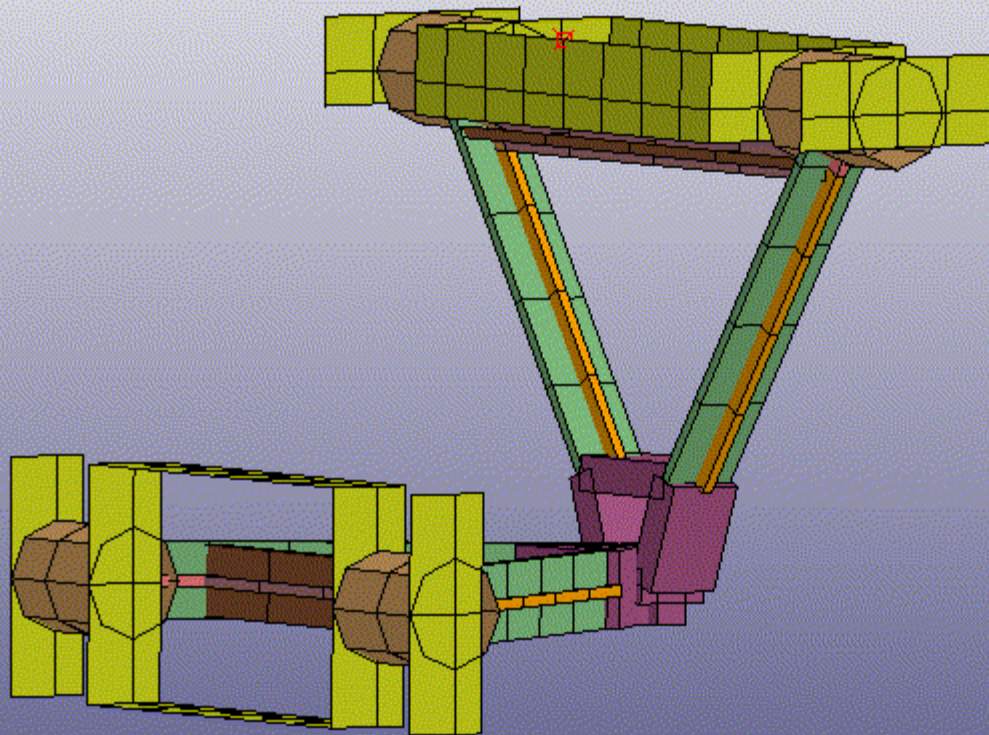
Buff1 SelectInfo
All Rm Kp SortBy
All None Rev
Auto Apply Done

Remove/Keep parts inside a user defined region

Fast Render...

MPP Domain Decomp. Error: Constraint is Defunct / Windshoe to Deck Connection is not working !

FSM_bridge_17.05.2018_mm_kg_ms_KN
Time = 0



MPP Dom. Decomp.: How to Fix it Manually?

FSM_13.05.2018.k x

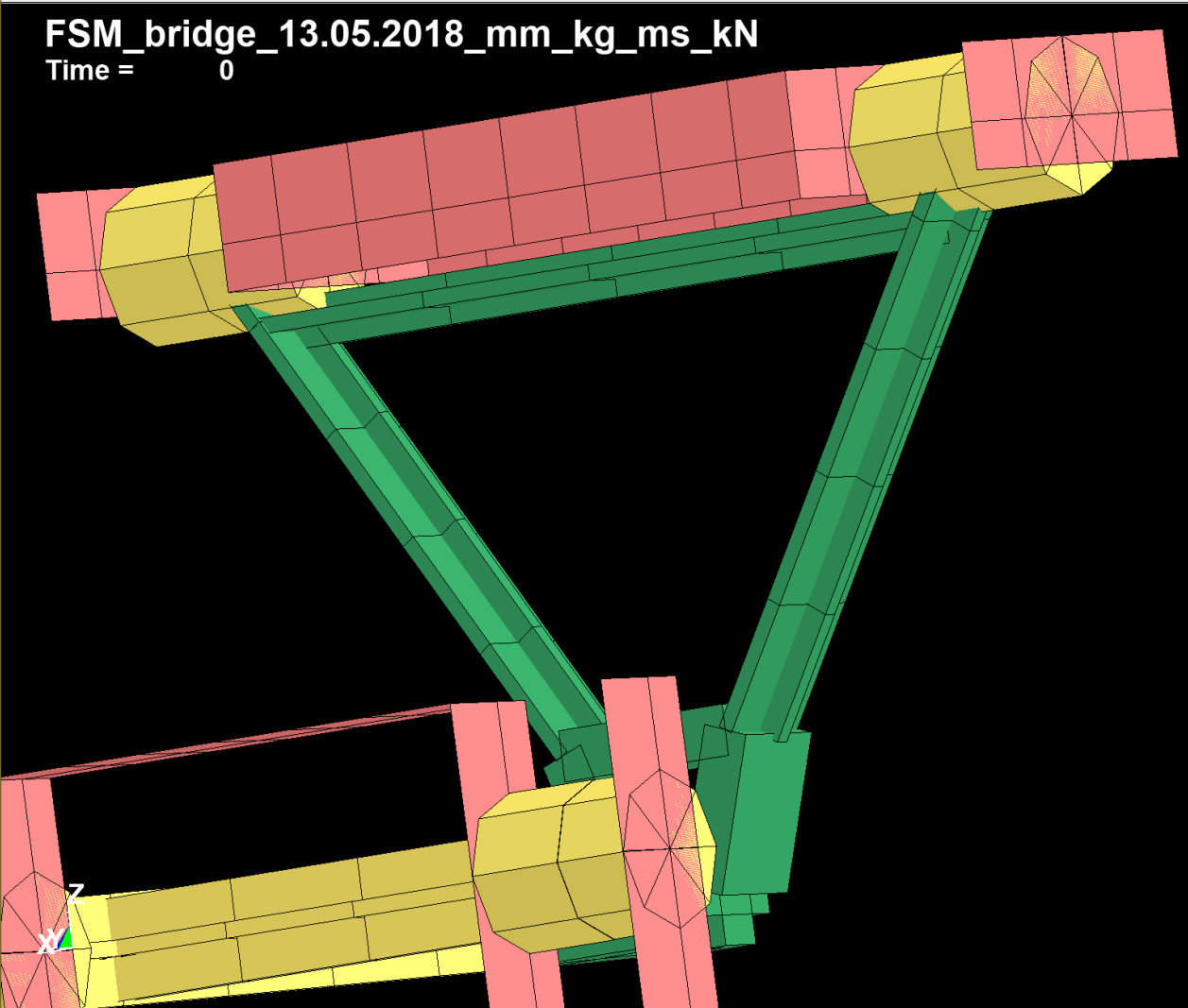
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2  $# Created on May-13-2018 (22:51:37)
3  *KEYWORD MEMORY=1950000000
4  *TITLE
5  $# title
6  FSM_bridge_13.05.2018_mm_kg_ms_kN
7  $# *CONTROL_MPP_DECOMPOSITION_NUMPROC
8  $# 96
9  $# *CONTROL_MPP_DECOMPOSITION_SHOW
10 *CONTROL_MPP_DECOMPOSITION_OUTDECOMP
11 1
12 *CONTROL_MPP_DECOMPOSITION_ARRANGE_PARTS
13 100 11
14 *SET_PART_LIST
15 $# sid da1 da2 da3 da4 solver
16 100 0.0 0.0 0.0 0.0 OMECH
17 $# pid1 pid2
18 101 102
19 *CONTROL_ENERGY
20 $# hgen rwen slnten rylen
21 1 1 1 2
22 *CONTROL_IMPLICIT_GENERAL
23 $# imflag dt0 imform nsbs igs cnstn form zero_v
24 -2 2499.0 2 1 1 0 0 0
25 *CONTROL_IMPLICIT_SOLVER
26 $# lsolvr lprint
27 4 3
28 $# lcpack mtxdmp
```


MPP Dom. Decomp. Problem Manually Fixed

LS-PrePost(R) V4.3 (Beta) - 24Nov2015(09:00)-64bit N:\4d.fsm.second.paper\mppmod\d3plot

File Misc. Toggle Background Applications Settings Help

FSM_bridge_13.05.2018_mm_kg_ms_kN
Time = 0



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SPlane	Setting	State
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Find	Ident	ASCII
Fcomp	History	Views
Appear	Color	Model
Group	Blank	SelPar

1 2 3 4 5 6 7 D

-Part Selection

- Md1 ▾ B 66
- B 67
- Beam B 68
- Shell B 69
- Solid B 70
- Tshell B 71
- CNRB B 72
- B 75
- Mass B 78
- B 81
- Disc B 84
- SBelt B 90
- B 93
- Inerta B 94
- Rsurf B 95
- Sphnd B 96
- S 97
- Fluid/ S 98
- NURB S 99
- DiscS S 100
- S 101
- MSms S 102
- Singl S 103
- S 104
- Area S 105
- Poly S 106
- S 107
- Save S 108
- S 109
- Load S 110
- S 111

Buff1 ▾

All ▾ SelectInfo

Rm Kp SortBy

All None Rev

Auto Apply Done

Fast Render...

Title	Off	Tims	Triad	Bcolr	Unode	Frin	Isos	Lcon	Acen	Zin	+10	Rx	Deon	Spart	Top	Front	Right	Redw	Home
Hide	Shad	View	Wire	Feat	Edge	Grid	Mesh	Shrn	Pcen	Zout	//	Clp	All	Rpart	Bottom	Back	Left	Anim	Reset

BDC

First 1 Last 1 Inc 1 Loop

- < > + ||

SF 1.0 Time 0

No.of Div State# 1

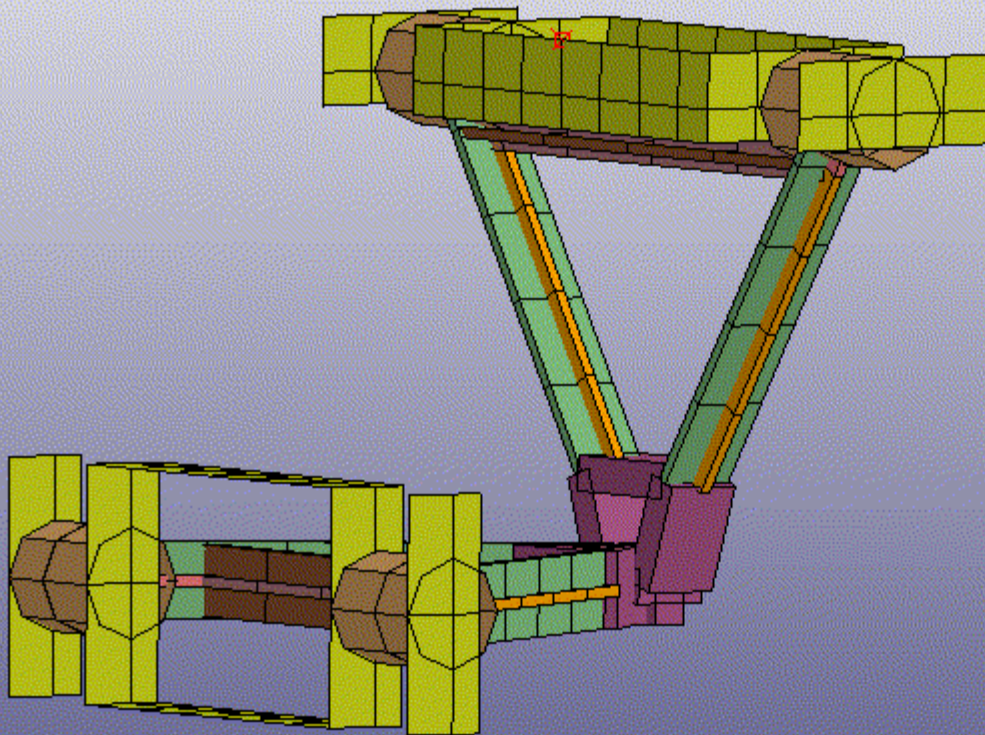
Ev 1 Done

selectpart on B95/0 B96/0 S192/0

Select/Deselect (Use Ctrl key for multiple selection)

MPP Domain Decomp. Correction for Constraints: Problem Fixed

FSM_bridge_17.05.2018_mm_kg_ms_kN
Time = 0



Conclusions

- **Shell model and ambient vibration measurements are in agreement for a wide range of eigenmodes, including the torsional model**
- **Earthquake/Erdbeben simulations demonstrate the possibility of deck-to-tower impact for strong ground motions.**
- **Future work will involve the investigation of large vibrations dampers that could be installed in the bridge. Currently, the larger-span Osmangazi Izmit Bay Crossing Bridge has vibrations dampers installed, and the bridge is currently in service.**

Further Information

- **Refereed paper in an archival journal:**

Kilic, S. A., Raatschen, H. J. , Körfgen, B., Apaydin, N. M., Astaneh-Asl, A., "FE Model of the Fatih Sultan Mehmet Suspension Bridge Using Thin Shell Finite Elements", Ara. Jou. Sci. Eng., Springer, 42(3), 1103-1116, March 2017.

**Thank you
for your
attention!**

Questions?