# FINITE ELEMENT ANALYSIS

# OF JOINTS, BEARINGS AND SEISMIC SYSTEMS

Terry M J Cakebread, LUSAS.

**Biography:** Since 2004 **Terry Cakebread** has been the Vice President (North America) of LUSAS and is in charge of American Operations involving training, sales and support to clients. He has a BSc Honors Degree in Civil Engineering from Southampton University and is a Chartered Civil Engineer and a Member of the Institution of Civil Engineers (MICE) in the UK. He has delivered many lectures on Finite Element Analysis and the benefits that it brings to those involved in structural analysis and load rating.

## ABSTRACT

This paper describes and illustrates how advanced Finite Element Analysis (FEA) software has been used to computationally model joints, bearings and seismic systems on a variety of projects worldwide. Reference will be made to the software program, LUSAS[1], which has been developed progressively over the last 35 years and become one of the leading FEA software products for structural and bridge engineering analysis in use today.

The paper will illustrate the different ways that bearings can be modeled and cover:

- The relevance of using different finite element joint models in differing situations
- Different ways to model lift-off behavior (smooth contact or elastic-plastic joints)
- The use of more advanced joints for modeling lead rubber bearings and friction/pendulum bearings
- Why dampers and other seismic systems are employed and the methods of modeling them.

- Some more detailed bearing models including carrying out bearing repairs in situ and ways of modeling detailed bearing models with full contact behavior.

**Keywords:** Finite Element Analysis, Global Modeling, Local Modeling, Joints, Bearings, Seismic Systems

## INTRODUCTION

Finite element analysis (FEA) first really came into use in the 1960s where analysis was carried out on mainframe computers. It has come a long way since then. On today's range of PCs and laptops engineers can model and predict with a fair degree of accuracy the response of structures that incorporate increasingly sophisticated joints and bearings and seismic systems to ensure that they articulate properly under a wide range of static, construction, thermal and dynamic/earthquake loading.

Traditionally bearings and joints were not modeled well, meaning that often basic assumptions were made about their behavior. As a result the finite element 'boundary conditions' that were used were often poorly defined leading to incorrect results. Nowadays designers of FEA software try to make the modeling of these complex joints easier so that the designer can more readily model something closer to reality. A range of ways of modeling, utilizing basic and advanced joint models are described in this paper. The response of a structure can be assessed well with a global model using joints elements. Localized modeling of the joint or bearing itself can also be carried out either to derive joint properties for use in a global analysis or to investigate local effects.

## RESEARCH SIGNIFICANCE

Advanced Finite element analysis provides researchers and practicing engineers with the tools to accurately model the behavior of test specimens and real structures in the field. Finite Element models can be calibrated or fine-tuned against either measured or experimental data to enable more accurate predictions of response to be made for a wide range of anticipated or unexpected situations or to better understand structural distress or failure.

## FINITE ELEMENT TOOLS FOR MODELING JOINTS

### Linear and Nonlinear Joints

In their simplest form joint elements can be used to connect two or more nodes in a finite element model with springs having translational and rotational stiffness. Linear joint models can be defined by a spring stiffness that corresponds to each local freedom or by specifying a set of general properties for spring stiffness, mass, friction, coefficient of linear expansion and damping factor. Sometimes these are just required to model lift-off support situations. To facilitate this in some software, simple lift-off behavior can be modeled for one component like a bridge deck with a support condition which allows lift-off as seen in **Fig 1**. However, in LUSAS lift-off or contact is checked for in each load case so, in effect, it is carrying out a nonlinear lift-off procedure. This means that in one case you can have lift-off and in the next loadcase you may not. More sophisticated joints will be required if you have lift-off between two components in the model such as a deck and abutments or if one has initial gaps, contact properties, an associated mass and damping, and other nonlinear behavior. Joint material models are used in conjunction with joint elements to define the material properties for linear and nonlinear joint models and for hysteretic behavior or piecewise linear behavior. Nonlinear joint models[2] typically provided in finite element software, and as shown in **Fig. 2**, allow for elasto-plastic uniform tension and compression with isotropic hardening where equal tension and compression yield conditions are assumed; elasto-plastic general joints with isotropic hardening for unequal tension and compression yield conditions; smooth contact with an initial gap and frictional contact with an initial gap. Both smooth contact and frictional contact joints can be used for lift-off or hook contact by using appropriate stiffnesses, gap and yield force.

**Joint elements to model failure in structures:**

For pushover and large displacement analysis often joint models are used to model the behavior of a system. These are invariably hysteretic joint models to mimic the behavior of structural connections such as reinforced concrete, steel and timber. There are a wide range of these joint types available as seen in **Fig. 3** and are generally outside the scope of this paper. More details are available in the LUSAS[1] manual.

**Seismic Isolators**

These more complex joint models exist to control the damage impact of seismic activity on structures. These joint types may be summarized as being used for seismic isolation, energy dissipation, or to model an active control system. Various types of isolator are available as shown in **Fig. 4** including High Damping Rubber Bearings (HDRB) – the most commonly used elastomeric bearings; Lead Rubber Bearings (LRB) with plastic yield and biaxial hysteretic behavior as modeled using the Bouc-Wen[3] model; and Sliding/Frictional Pendulum Systems (FPS) with pressure and velocity dependent friction coefficient and biaxial hysteretic behavior. The idealized behavior of an FPS bearing is shown but in reality this follows the hysteric behavior of lead rubber bearings. Hysteresis is that highly nonlinear phenomenon that occurs in systems that possess memory and, as a result, all isolator types shown are incorporated into LUSAS as nonlinear joint models. Finally the triple friction pendulum bearing has differing hysteresis behavior depending upon which part of the system is moving. It has 3 pendulum movements with 5 stages of behavior. So under a small earthquake the first mechanism is formed under high stiffness, the second is formed with moderate stiffness with a moderate earthquake, and the third mechanism is formed under a strong earthquake where the tension stiffness is small so that large movements can be accommodated. The Triple friction pendulum bearing[4] is also designed to reduce ultimate displacement under very strong earthquakes. This multi state behavior can be represented by an assemblage of springs as illustrated in **Fig 4** or with a special joint which is more reliable for 3D behavior.

### Viscous Dampers

Visco-elastic dampers can be modeled using the four parameter solid model shown in **Fig. 5** which comprises 3 springs and a dashpot. If only K1 exists then this becomes the Kelvin-Voigt or Kelvin Model. If all springs are absent it then reverts to a simple dash-pot damping model. If K1 does not exist and K2 and/or K3 exist it becomes a Maxwell model.

## GLOBAL MODELING OF JOINTS AND BEARINGS

### Pin and hanger joints

Pin and hanger joints, as used with suspended spans on bridges, are a fairly simple joint to model in the global sense. The Old San Francisco Oakland Bay Bridge East Span shown in **Fig. 6** is one such structure that incorporates a pin-supported suspended span. When the bridge owner, Caltrans, employed Silverado Contractors, Inc. and California Engineering Contractors, Inc. to deconstruct the bridge they used Foothills Bridge Co. to model the deconstruction sequence of the bridge. Foothills firstly built a single global model representing the current in-service configuration using accurate member cross-sections and weights. The original 1930's design and fabrication drawings included stress sheets that provided the original designer's member forces as well as pier reactions. This information allowed the FEA model to be "benchmarked" against the original design and ensured that bridge member forces and reactions could be reliably predicted. At first glance, it appeared that the erection sequence would not have much bearing on the output of the model. However, as the erection sequence was studied in greater detail, it was found that during several stages of construction the bridge was jacked at various locations to allow for correct fit-up of members and to ensure that the deformed shape of the bridge was correct. This jacking resulted in locked-in erection forces that needed to be considered in the model.

The proposed dismantling sequence approximately reversed the sequence used to construct the bridge. Caltrans made available a detailed description of bridge erection procedures so that the subtleties of the bridge erection could be modeled and accounted for in the dismantling procedure. All dismantling was generally carried out using hydraulic cranes and excavators located on the bridge lower deck. Each dismantling stage in the model considered the positioning of the equipment and removal of truss members.

Key aspects of the dismantling sequence for which LUSAS was particularly useful were:

- Carrying out "The cut" at midspan.
- Indicating where temporary truss members and local tension release devices were needed.
- Indicating when temporary support towers and temporary truss members were required in the anchor spans.

The bridge was constructed with the two halves of the cantilever extending to midspan, the opposing halves cantilevering 700 ft (214m) from each of the main piers. Jacks on the upper chord and lower chord adjusted the position of the bridge so that the two halves could be aligned and connected. After the bridge was connected at midspan, the suspended span was "swung" by releasing the upper chord at both ends of the suspended span, allowing the bridge to relax into its designed configuration. The swinging resulted in the 576 ft (176m) suspended span simply hanging from the tips of the opposing cantilever arms. The contractor opted to remove the cantilevered structure by substantially reversing the original engineered erection sequence. To accomplish this, the main span needed first to be converted from its relaxed "swung" configuration into two independent cantilevers, then severed at midspan prior to proceeding with the dismantling of the opposing halves. This procedure of severing the main span became known to the engineers as "The cut". Before this could be done, the upper chord at each end of the suspended span needed to be re-engaged to convert the suspended span into extensions of the cantilever, and then be jacked to relieve the forces in the suspended span. This would then allow the bridge to be cut at midspan without a large release of energy and minimal bridge deflections. By using LUSAS to model this sequence they were able to provide the contractor with the required jacking forces and expected bridge displacements. At each end of the suspended span, the upper chord was jacked to approximately 2,000,000 lbs (8900kN) of force per truss, equating to a displacement of approximately 5" (125mm). Additionally, the lower chord was jacked with 250,000 lbs (1100kN) force in each truss to relieve a small remaining tension in the lower chord prior to cutting. Bridge jacking was modeled by applying the jacking force and then activating the relevant bridge member in the model in order to hold the force (and displacement). The observed bridge displacements during upper chord jacking agreed favorably to those predicted by the LUSAS model, and provided the contractor with a high level of confidence in carrying out "The cut".

**Construction Sequencing**

For the new Broadway bridge in Little Rock, Arkansas designed by HNTB the two 440-foot steel basket handle arches will be constructed on top of falsework on barges and floated into position as shown in **Fig. 7** by Massman Construction with Genesis Structures modeling the erection engineering. The barges will then be flooded with the bridges coming to rest on the permanent bearings. When this happens, the bridge main tie girders will elongate due to the change in support conditions (falsework to permanent bearings). It is important with these structures to ensure that stresses are not built up in the stringers during any of the construction sequence so "Stringer Expansion" joint elements were used to prevent the stringers from taking on load as the bridge is set down on the permanent bearings and also when the deck concrete is poured. In each case the bridge elongated approximately 0.75" (19 mm). In addition for "Falsework Support" joint elements were used which included a friction value in the longitudinal direction. When the bridge is being lowered onto the permanent bearings and tries to elongate, the falsework picks up longitudinal load based on its longitudinal stiffness. In reality it is losing vertical force as the load is being transferred to the permanent bearings and therefore the friction values in the joint element allowed Genesis Structures to reduce the longitudinal force proportionally to the vertical load being supported and therefore reduce the design force in the towers… which is a real effect.

**Deconstruction Saddles**

Genesis Structures was employed by Massman Construction to model the deconstruction of the Paseo self-anchored suspension bridge in Kansas City, Missouri. The bridge originally built in 1954 had 616 ft (188m) main span with 308 ft (94m) end spans. The saddles at the top of the towers supported the main cables and translated 4.5" (115mm) during construction due to the longer central span. They were then locked down with steel plates. Over the 50+

year lifespan the deck was replaced and bearings raised so a LUSAS model was built as in **Fig. 8** of the saddles and joints to help predict the locked in stresses and the potential movement once the steel plate was cut in the deconstruction sequence. Jacks were put in place and the plate cut and the jacks slowly released. The actual movement was as predicted in all the saddles within ¼ " (6mm).

**Multiple Opening and Closing Joints**

To model lift-off and frictional sliding nonlinear contact joint elements are used. The foundation, stop-block and shear-key interfaces of a massive reinforced concrete caisson as used in a dock closure system in the UK as shown in **Fig. 9** were assessed in order to guarantee its safety under seismic loading. Additional joint elements were used to provide hydrodynamic mass and damping actions on the walls and base-interface respectively. Thin shell elements modeled the caisson cell walls and thick-shell elements modeled the base. Ground acceleration history for a UK hard site provided the seismic input with increments of 0.005 second being used for each time step. Hydrostatic pressure and self-weight were applied as initial static loads. Hydrodynamic forces from the water enclosed in the cells were simulated by locating joint elements at each node on each wall and assigning directional masses calculated using the Westergaard[5] model. Acceleration histories were applied to the foundation to drive the ensuing dynamic analysis. Values of frictional damping at the contact interface of 3%; structural damping of 5%; and interface damping of 2% to simulate the effect of the fluid between the base and the dock floor were used in the analyses. The analysis clearly showed the caisson had adequate structural capacity to withstand a seismic event and that the seals could accommodate the displacements expected.

### Viscous Damping

Nonlinear joint elements modeled the elastomeric bearings and seismic dampers of a 1108m long, multi-span bridge structure in the Mediterranean region, as shown in **Fig. 10**, and enabled design forces to be expected in the case of an earthquake to be assessed to Eurocode EC8. This prestressed reinforced concrete road bridge comprised both straight and curved sections with an expansion joint midway along its length. In LUSAS, engineering thick beam elements (Timoshenko beams) defined at the respective centroid of each structural component modeled the reinforced concrete deck. Connection between deck and elastomeric bearings and between the top of the piers and elastomeric bearings was made using nominally stiff members of negligible mass. These represented rigid links between the centroids of components and were defined with negligible mass so as not to contribute to the dynamic behavior of the bridge. Two longitudinal dampers were located at the 1st abutment and transverse dampers, located at every 3rd pier along the bridge, required an additional stiff member arrangement. Eigenvalue analyses on both bridge structures found that 225 structural modes were required to meet the 95% mass participation factor value required prior to carrying out a subsequent spectral response analyses using EC8 design spectra. Three nonlinear transient dynamic analyses were performed on each bridge using combinations of acceleration time-history dataset pairs in the longitudinal and transverse directions, as used by the bridge designers. **Fig. 11** shows a typical transverse force time history plot produced. Good correlation of results was achieved for both the spectral response and transient dynamics analyses, verifying the modeling techniques used by the original designers and the viscous damping capabilities of the LUSAS model.

## LOCALIZED MODELING OF JOINTS AND BEARINGS

### Concrete Deck half-joints (sometimes referred to as dapped ends)

Half-joints, initially introduced into concrete bridge decks as a means of simplifying design and construction operations are known to be vulnerable to concrete and reinforcement deterioration from chloride attack in the event of deck expansion joint failure, and also cause concern because they are not easily accessible for inspection or maintenance. In addition, on older structures, the half-joints as designed may not be code-compliant with today's standards and may require assessment for increased modern vehicle loadings. The Kingston Bridge in Glasgow, UK, is one such bridge with half-joints that attracted investigation.[6] The bridge carries an average of around 180,000 vehicles per day, and is one of the busiest in Europe. The post-tensioned, table-top spans and reinforced concrete box girder suspended spans of the approach ramps include numerous half-joints designed in accordance with late 1960s standards. These are shown schematically in **Fig. 12**. Dimensions of half-joint nibs vary but are generally in the order of 24" (600mm) deep x 18" (450mm) wide. An assessment showed that some of the half-joints were not compliant with modern codes and so, in light of a potential inadequacy, a destructive load test was undertaken on a typical half-joint on a ramp that was being demolished and replaced as part of other work taking place on the structure. The data obtained demonstrated significant capacity for the half-joint above that predicted by the assessment codes. The load test results were then used to calibrate a LUSAS nonlinear finite element model of the tested half-joint using a multi-crack concrete model. Once proved, various derivative models were used to reassess all half-joints in the Kingston Bridge, showing actual capacities were significantly higher than those calculated from the assessment codes and sufficient to sustain the assessment loading.

## Collapse Analysis of Bridge Bearings

Even back in 1995 bearings were being analyzed using finite element analysis. Then, UK Consultant Hyder (now Arcadis) had to carry out collapse analysis of fabricated steel 'trestle' bridge bearings, as used on the M5 road bridge at Avonmouth, and predict their ultimate strength both with and without strengthening modifications. Initial FEA models assessed the performance of both shell and solid element idealizations. Final all-solid models similar in nature to **Fig. 13** included geometric, material and contact nonlinear effects. With experimental data (load-strain measurements) being supplied very close agreement between measured and calculated values of ultimate load could be seen. The analysis also clearly showed that the failure mode was plastic collapse with elastic buckling occurring at a much higher load. Results were used by Hyder to help determine which bearings would require strengthening for increased bridge capacity.

### Contact Analysis of bearings

Sometimes solid models are required to model the contact analysis of bearings. Examples include bearings often used in moveable bridges such as Gateshead Millennium bridge **Fig.14.** In order to carry out these models you need to have advanced 3D elements and good meshing algorithms, and often contact analysis.

## OTHER FE TOOLS FOR MODELING CONTACT INTERFACES

Two other ways to model the interaction of structural parts or components concern the use of constraint equations, which constrain the movement of a geometric or nodal freedom in a particular way, and slidelines - also known as slidesurfaces - which model the interaction between contacting lines and surfaces.

### Constraint Equations

Constraint equations allow linear relationships between nodal freedoms to be set up. Constraint equations can be used to allow plane surfaces to remain plane while they may translate and/or rotate in space. Similarly straight lines can be constrained to remain straight, and different parts of a model can be connected so as to behave as if connected by rigid links. These geometric constraints are only valid for small displacements. Principal constraint types are: Displacement Control, Geometric, Cyclic , and Tied Mesh

**Slidelines/Slidesurfaces**

Slidelines/slidesurfaces can be used to tie dissimilar finite element meshes together and to model contact and impact problems in both 2D and 3D. They can be used as an alternative to joint elements or constraint equations and have advantages when there is no prior knowledge of the contact point. The properties of a slideline such as the contact stiffness, friction coefficient, temperature dependency etc are used to model the contact interaction between master and slave features. **Fig. 15** shows an example that includes both tied slidelines (to join the dissimilar meshes) and frictional slidelines to model the contact between the components. The former avoids the need for stepped mesh refinements between different mesh densities. **Fig. 16** shows a simplified contact application for a floating pontoon restrained by cables to two anchor blocks sitting on the sea bed. For this, only a frictional slideline is required.

## COMPARISON OF PREDICTED AND EXPERIMENTAL RESULTS

When measured or experimental data is available, results predicted by finite element analysis can be readily correlated. Once verified, fine-tuning of a model can be done or more advanced what-if modeling can take place – safe in the knowledge that the base model is accurate. Indeed the multiple analysis facility within LUSAS (where any property can be modified in a subsequent analysis and the results easily compared all in the same model) makes this an easier task to undertake.

## CONCLUSIONS

With the advanced finite element analysis tools available today it is possible to model all the different types of joint and bearing conditions. It is often important to do this to ensure the proper behavior is captured. Joint elements can be used in conjunction with line beam models when global modeling is carried out, or the bearings themselves can be modeled in detail using plane stress or detailed 3D solid models. Often, because of the very nature of the problems to be solved, the FEA software will need all the capabilities described in this paper including full nonlinear analysis and contact analysis. Finally, verification of FEA modeling results for a structure against measured or test data should be carried out for any model, and especially for complex models.

## ACKNOWLEDGEMENTS

The author wishes to acknowledge the help of the following in providing information to help putting together this paper:

Foothills Bridge Co – Nathan Miller

Genesis Structures - Dr David Byers

URS – Danny Boothman

LUSAS FEA Consultancy Team and numerous other members of staff

## REFERENCES

1. LUSAS Finite Element Analysis, LUSAS, Kingston upon Thames, UK.

2. Advanced Nonlinear Joints, Software Development Report SDR/LUSAS/381, LUSAS, Kingston upon Thames, UK, 2008

3. Wen, Y.K. Equivalent linearization for hysteretic systems under random excitations. ASME J. Appl. Mech. 47, 150-154, 1980.

4. Fenz, D.M. and Constantinou, M.C. (2008) Modeling triple friction pendulum bearings for response-history analysis *Earthquake Spectra* **24**(4): 1011–1028

5. Westergaard, H.M. Water pressure on dams earthquakes, ASCE, 1933.

6. Boothman, D., Leckie, S., MacGregor, I., Brodie, A., Assessment of Concrete Half-Joints using Non-linear Analysis, Proceedings of the ICE - Bridge Engineering, UK, Volume 161, Issue BE3. Pages 141-150

## FIGURES

**List of Figures:**

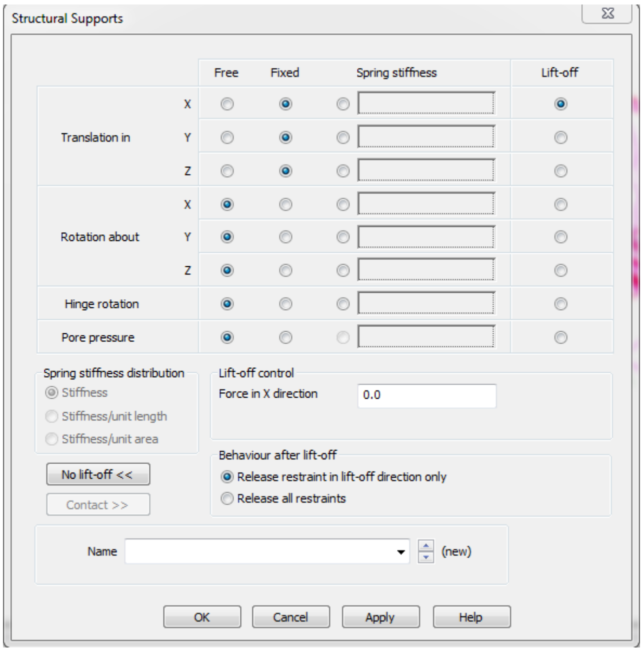
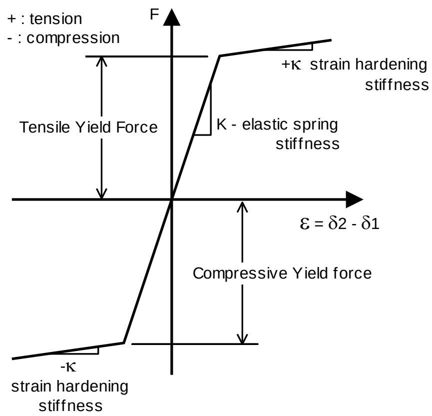
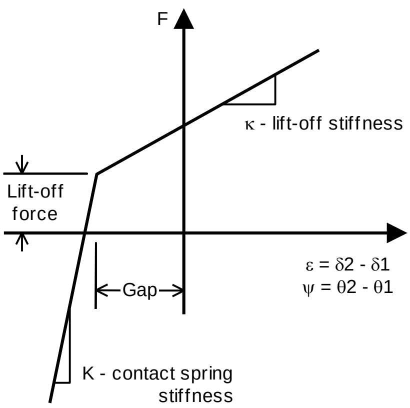


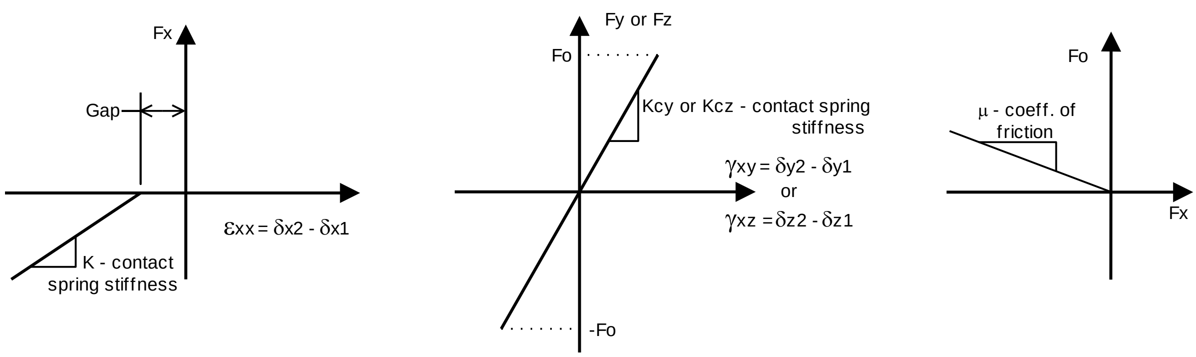

**Fig 1 – Lift-off control**




Elasto-plastic

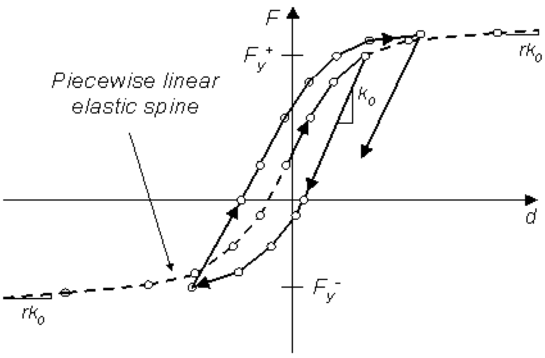



Smooth contact

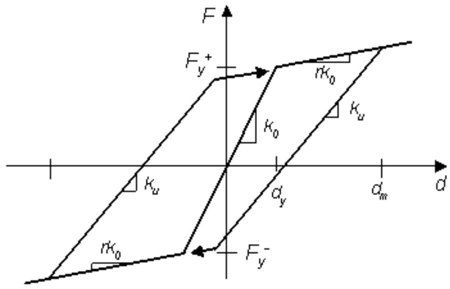



Frictional Contact

**Fig. 2–Elasto-plastic, smooth contact and frictional contact joint models.**

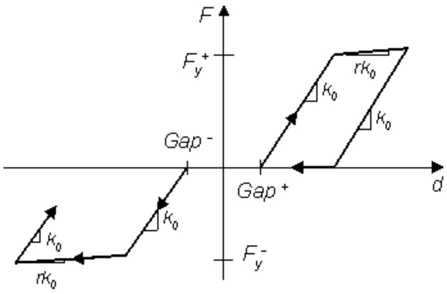



**Parallel reversal loading**



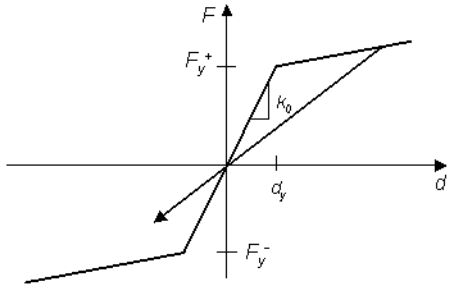

**Kinematic hardening**

This simplest form is the same as the Degrading bi-linear mode

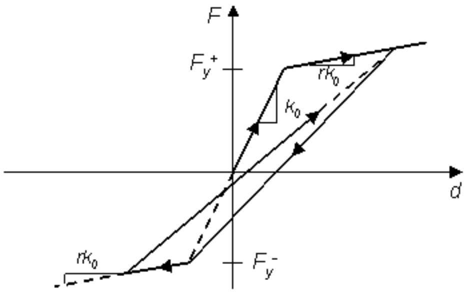



**Kinematic hardening with slackness**

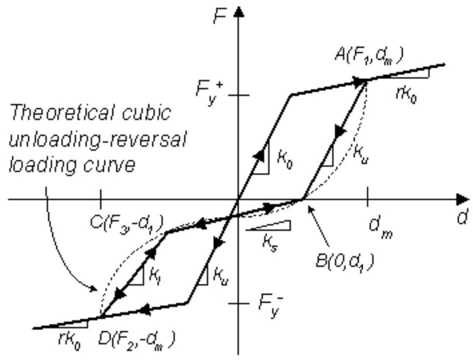
(This simplest form is the same as the Bi-linear with slackess model)



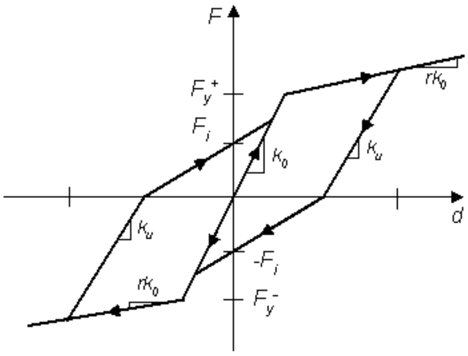

**Origin centred**



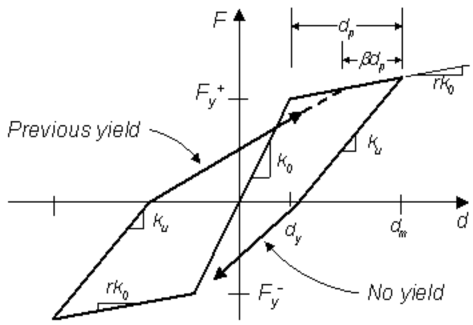

**Peak oriented**



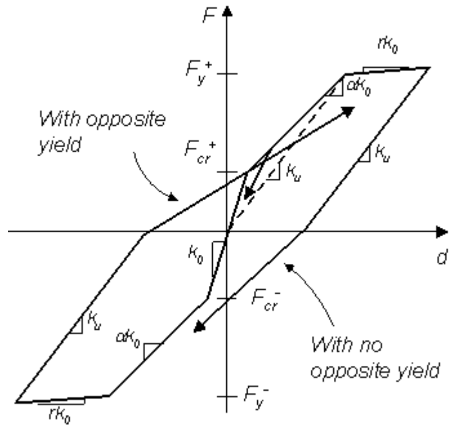

**Kivell**



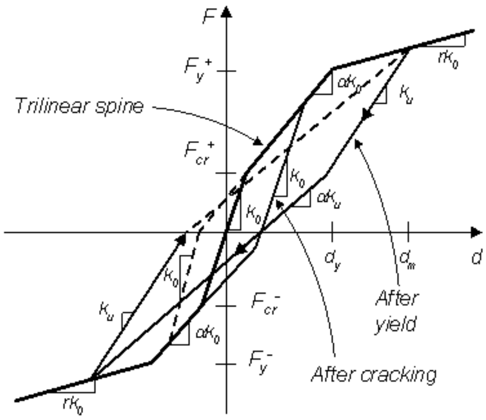

**Pinching point**



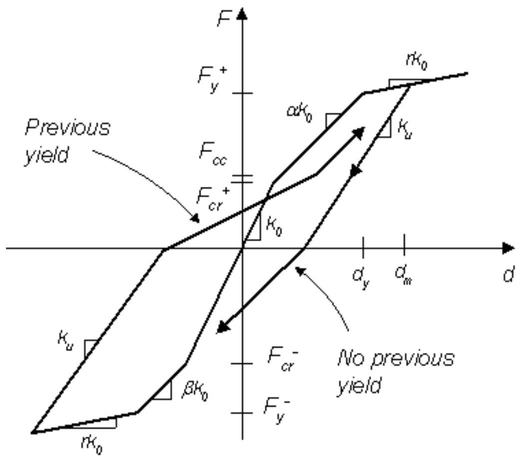

**Modified Takeda**



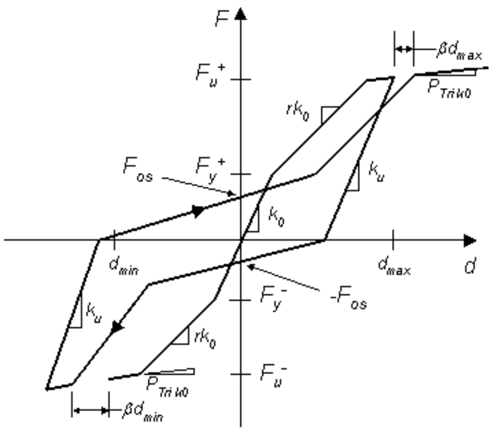

Muto outer




Fukada outer

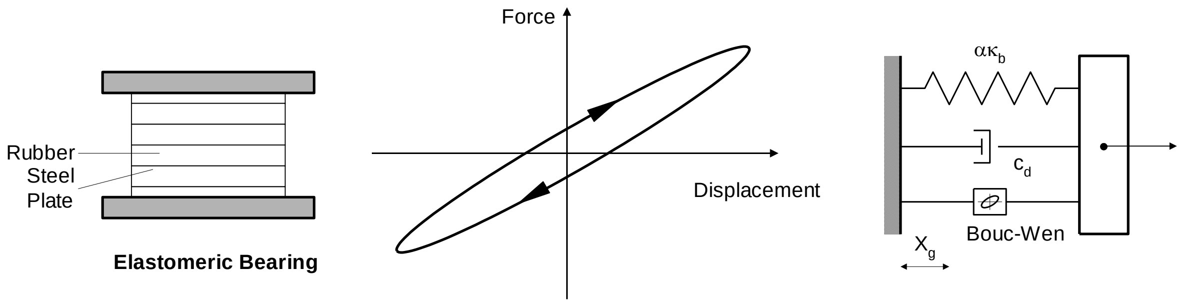



Sina outer

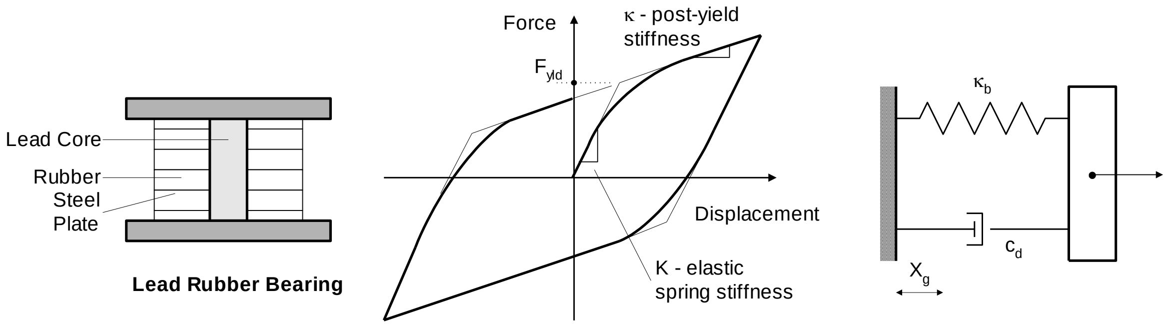



Stewart

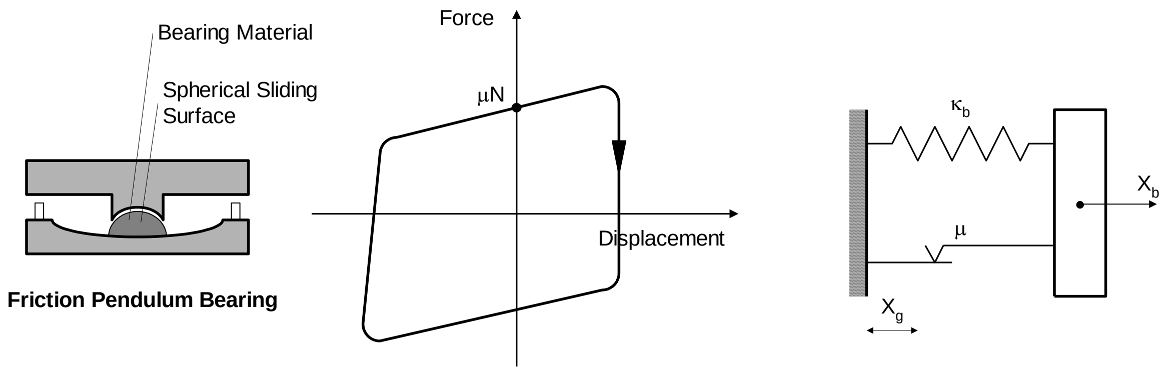
**Fig 3 – Hysteretic joint models to model potential failure in structures**



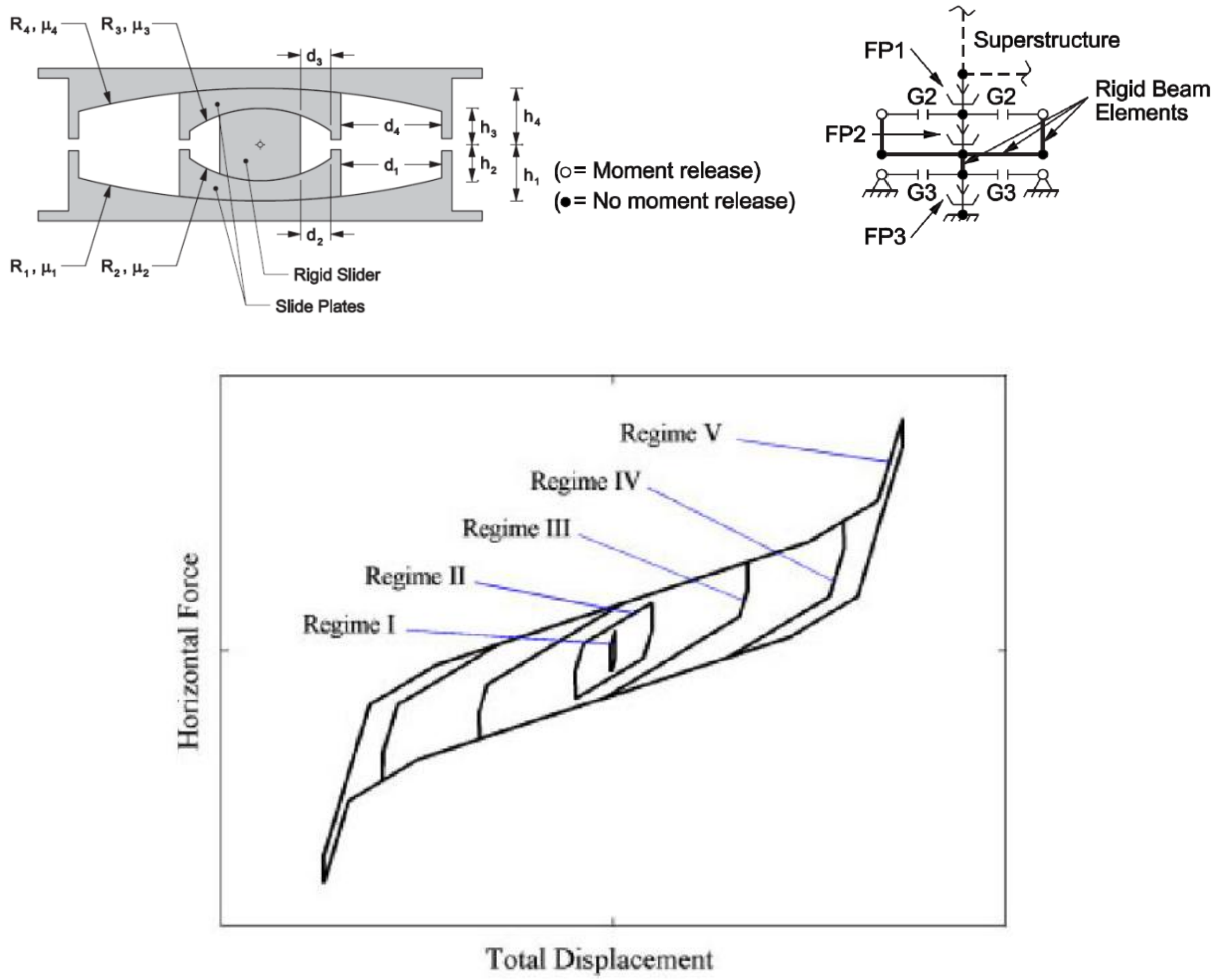

High damping rubber bearing, hysteretic behavior and schematic representation




Lead rubber bearing, hysteretic behavior and schematic representation




Friction pendulum bearing, hysteretic behavior and schematic representation




Triple friction pendulum bearing

**Fig. 4-Seismic isolator types**

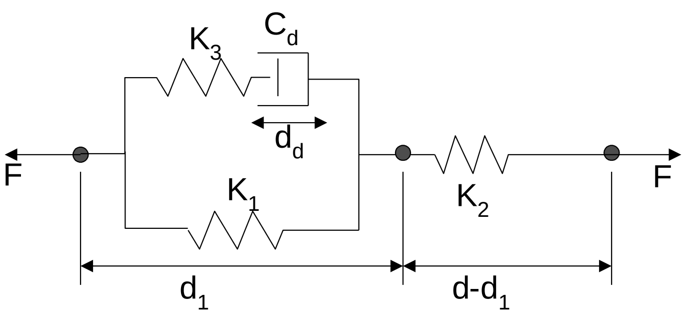
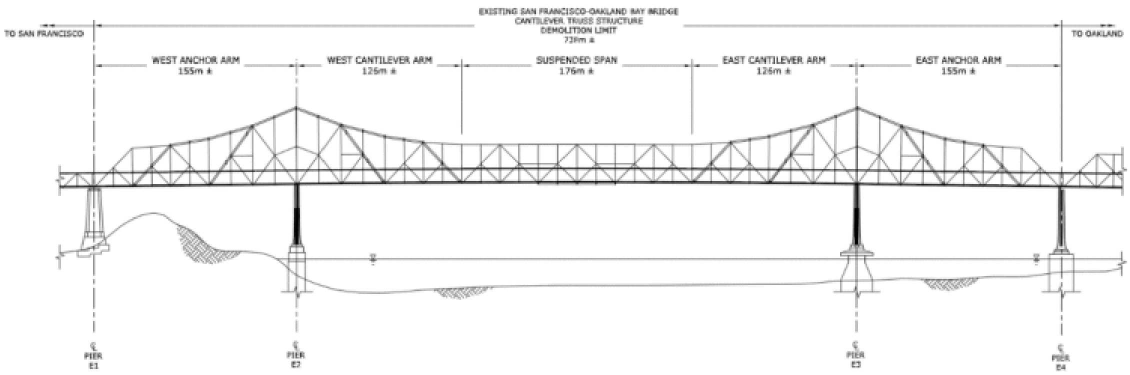
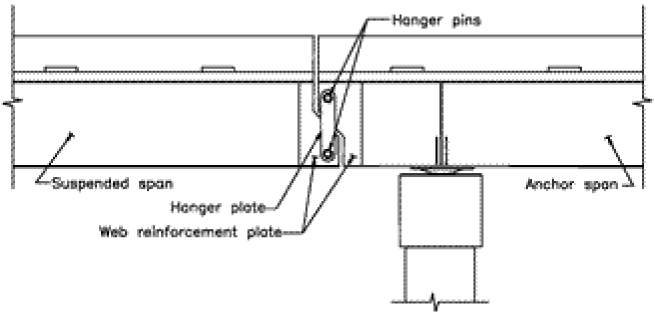



**Fig. 5– Four parameter solid model for visco-elastic bearings**




Layout and primary dimensions of the old East Main Span.




Typical pin and hanger joint

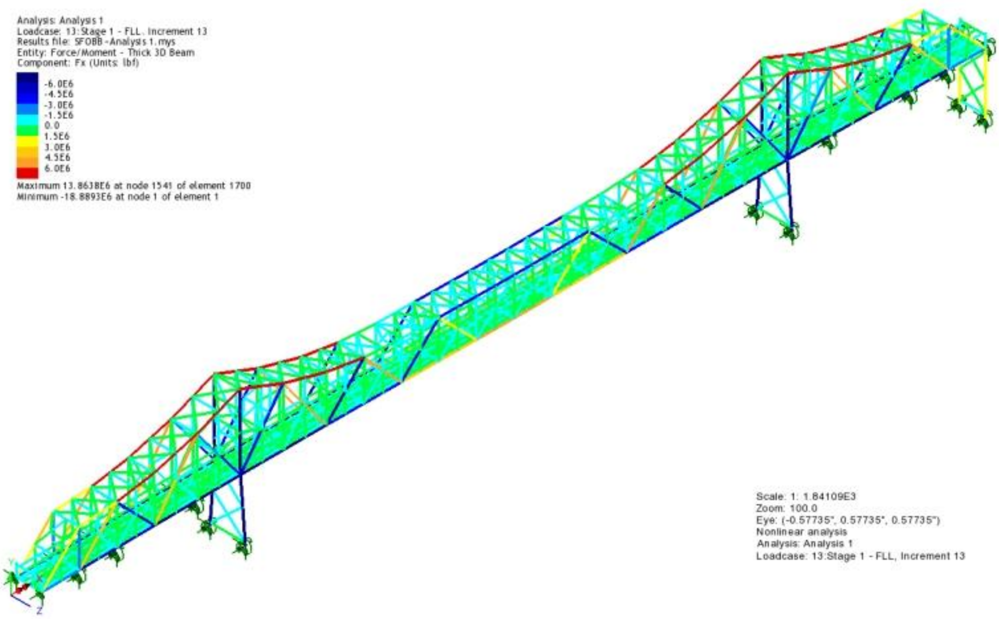
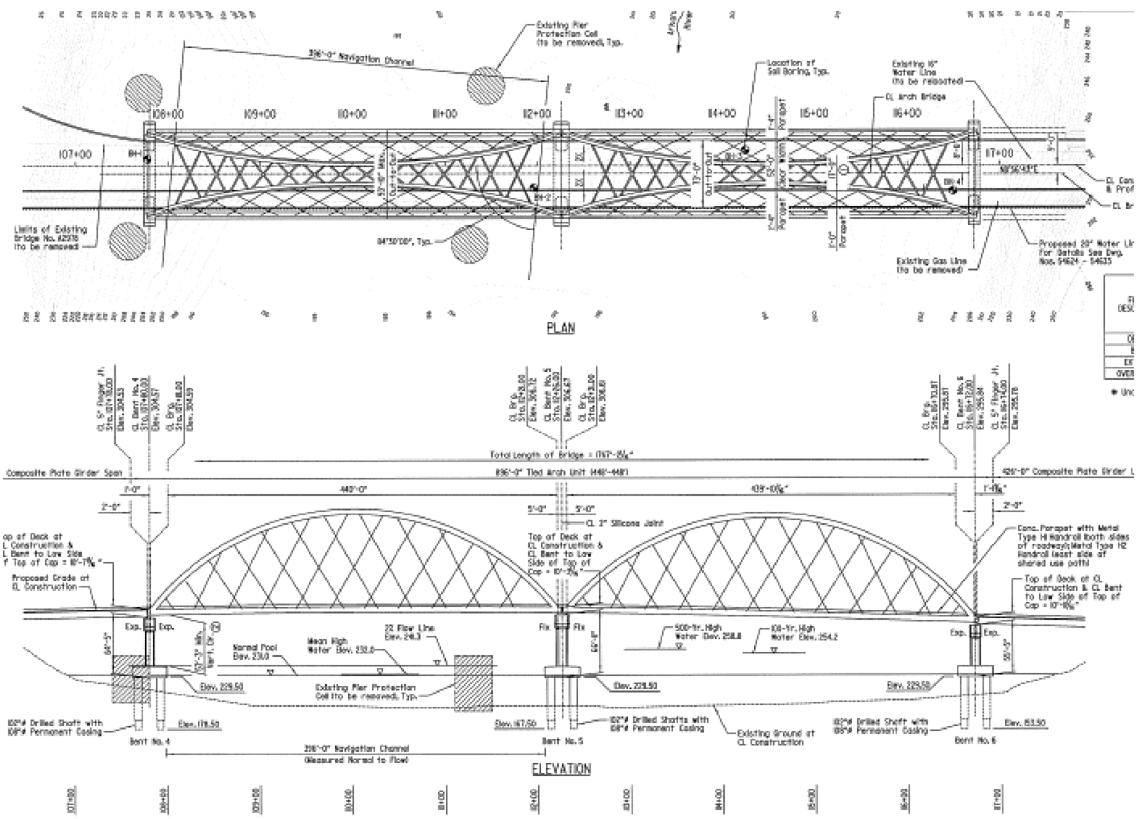
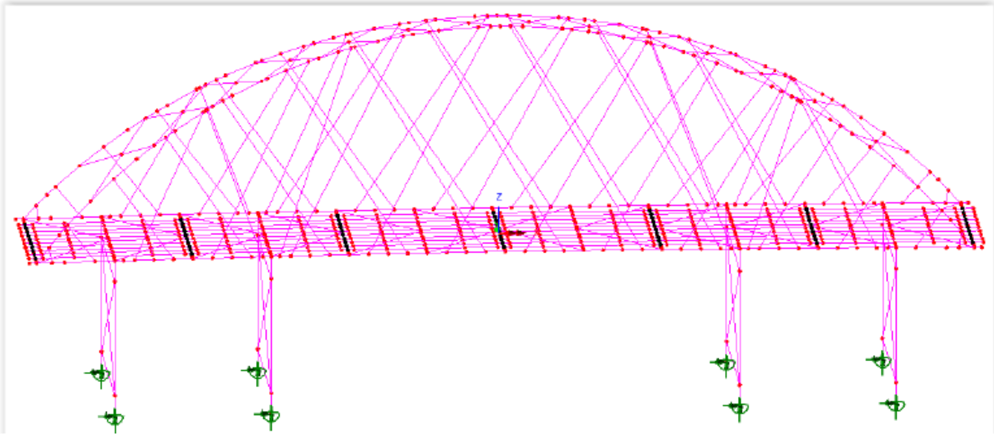


**Fig. 6– Old San Francisco Oakland Bay bridge with pin supported suspended span**



The stringer support at select floorbeams is modeled to accurately account for the slotted-hole longitudinal expansion connection with a "spring stiffness only" joint material.

The point assignments of this joint material are shown highlighted below.



The arch support on falsework is modeled to realistically limit the transfer of lateral force to the falsework as a function of the vertical load present with a "frictional contact" joint material.

The point assignments of this joint material are shown highlighted below.

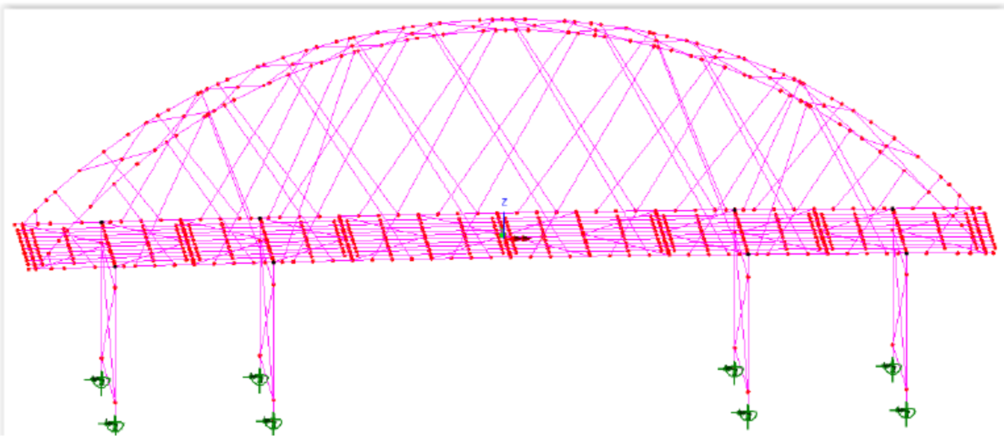
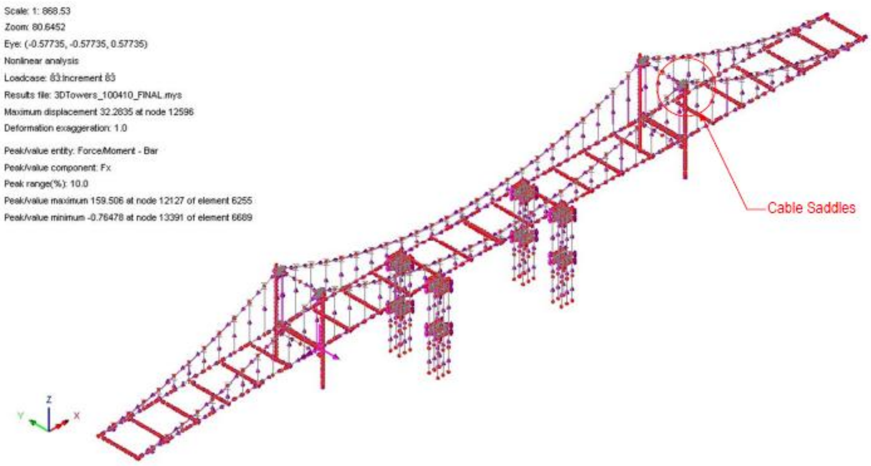
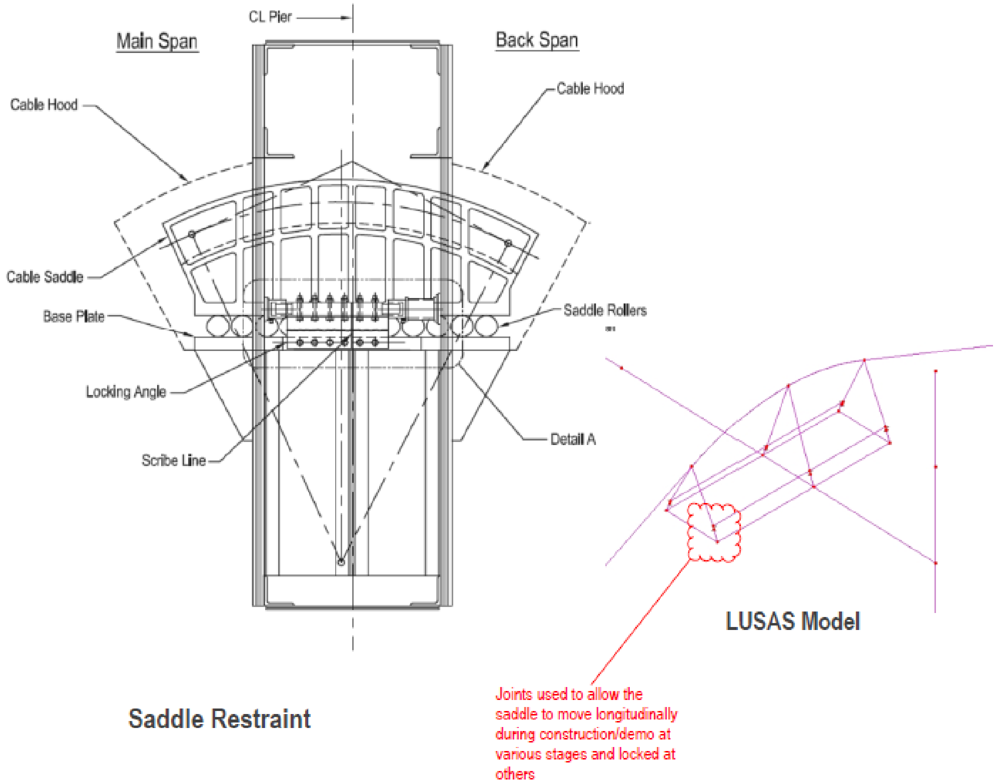


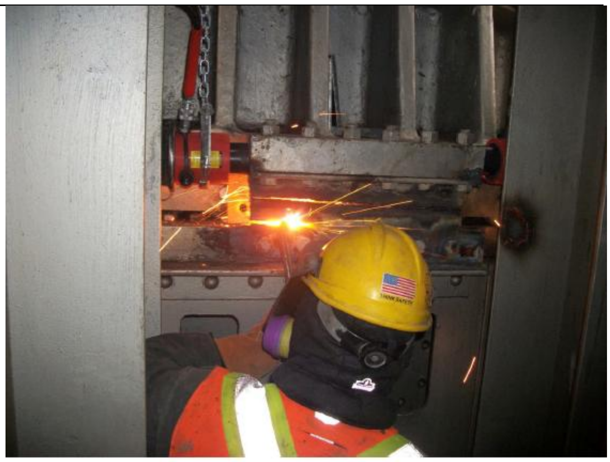
**Fig. 7- Broadway bridge in Little Rock, Arkansas**


**Analysis Model – Included original construction stages to establish existing stresses**




Saddle Restraint & Release



Saddle Restraint & Release

**Fig. 8- Paseo bridge demolition and cable saddle**

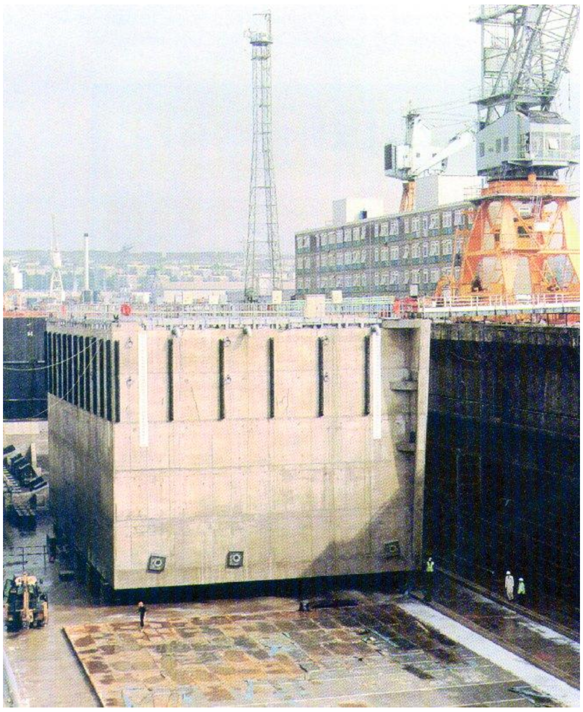


**Fig. 9– Dock caisson under construction**

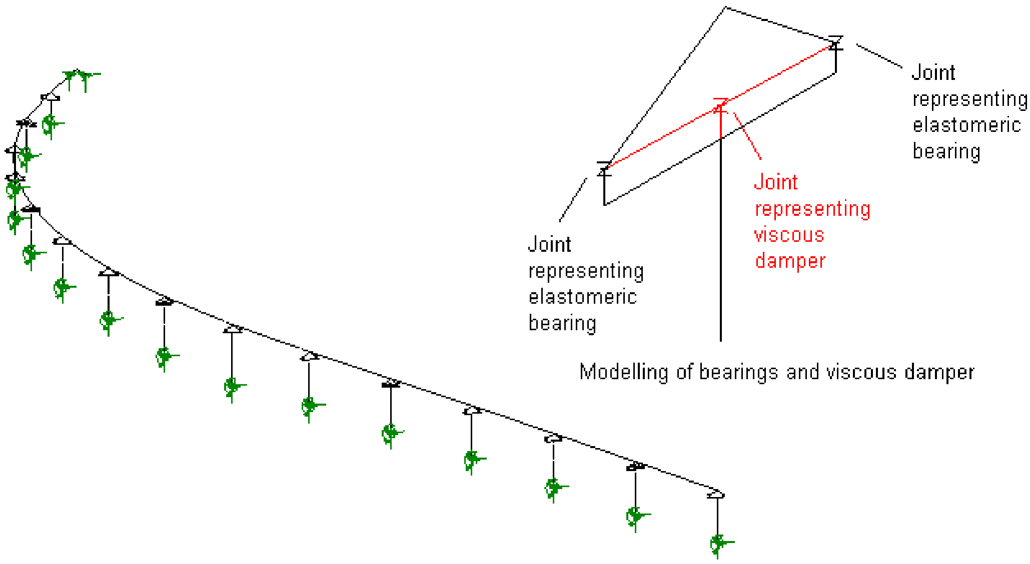



**Fig. 10– Global model of viscous damped road bridge**

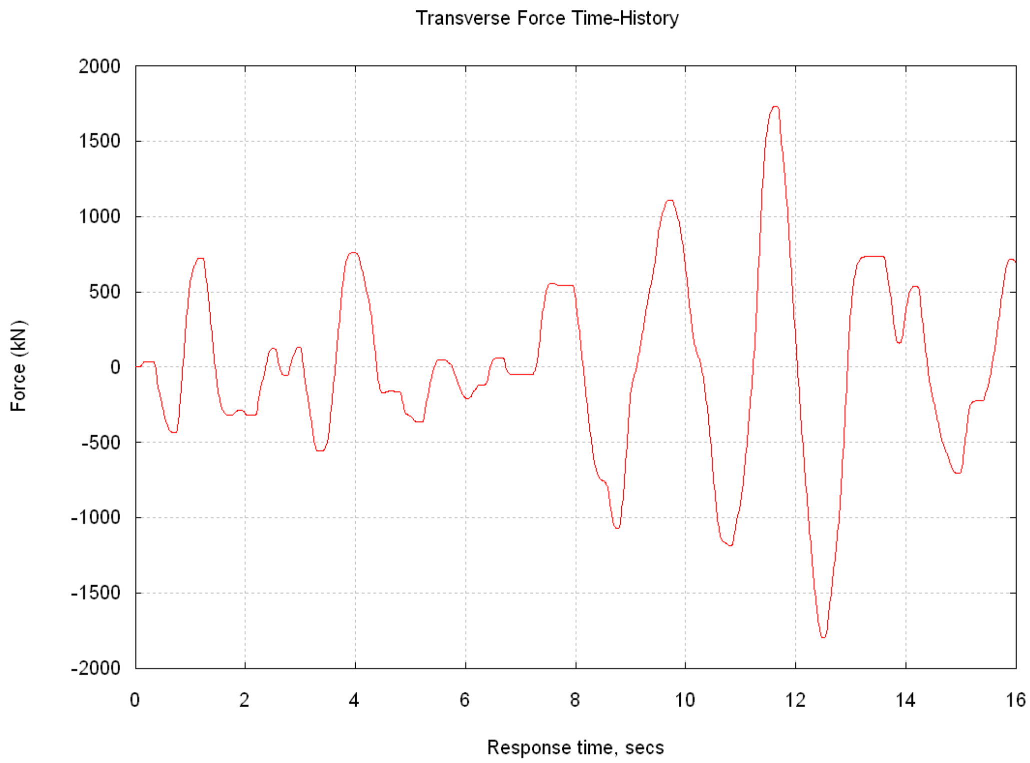



**Fig. 11– Typical transverse force time-history plot for selected pier**

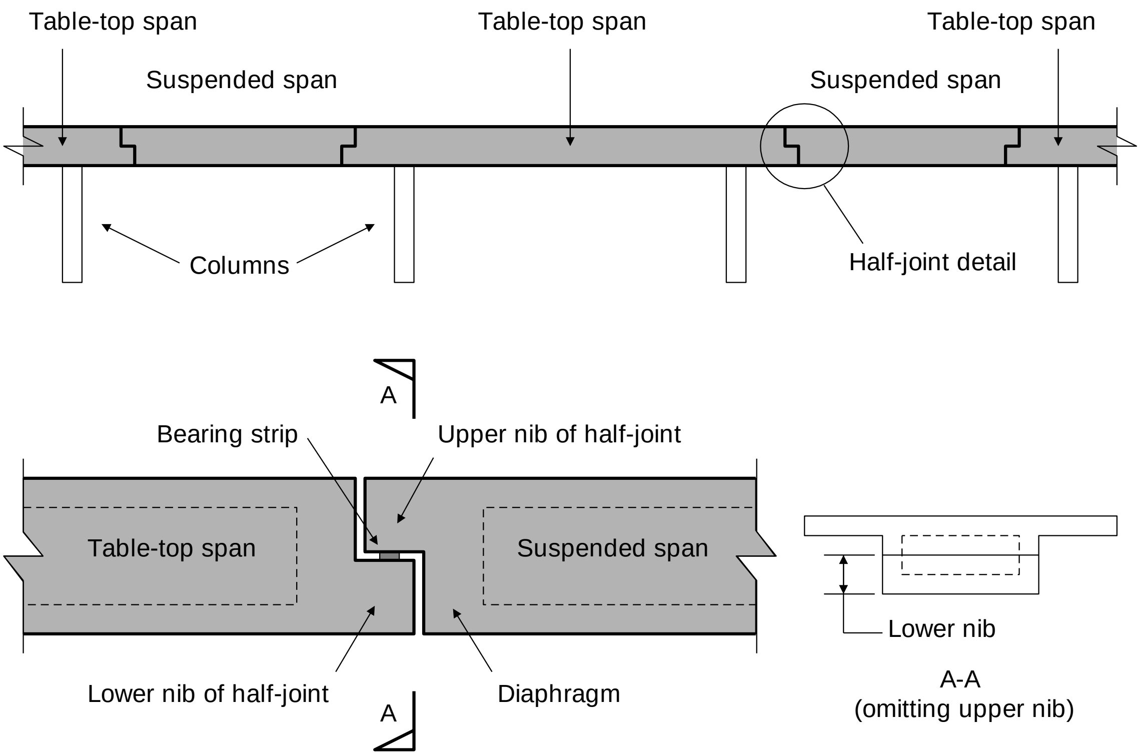



**Fig. 12-Schematic half-joint geometry for Kingston bridge approach ramps**

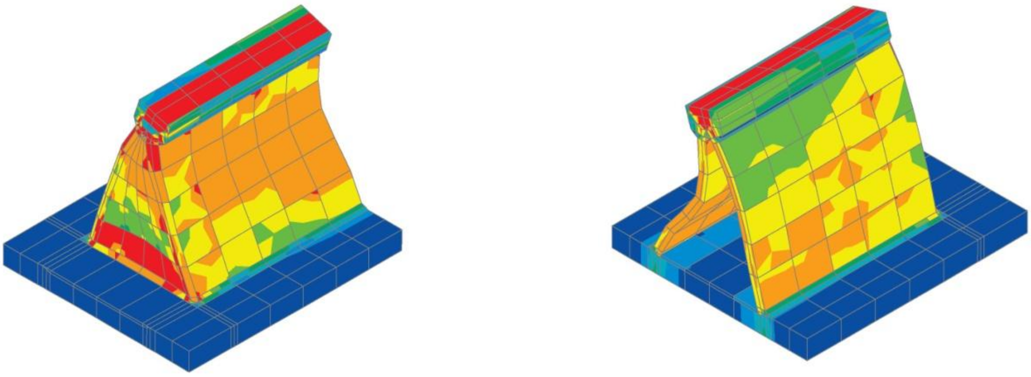


**Fig. 13– Half-model of trestle-type bridge bearing**

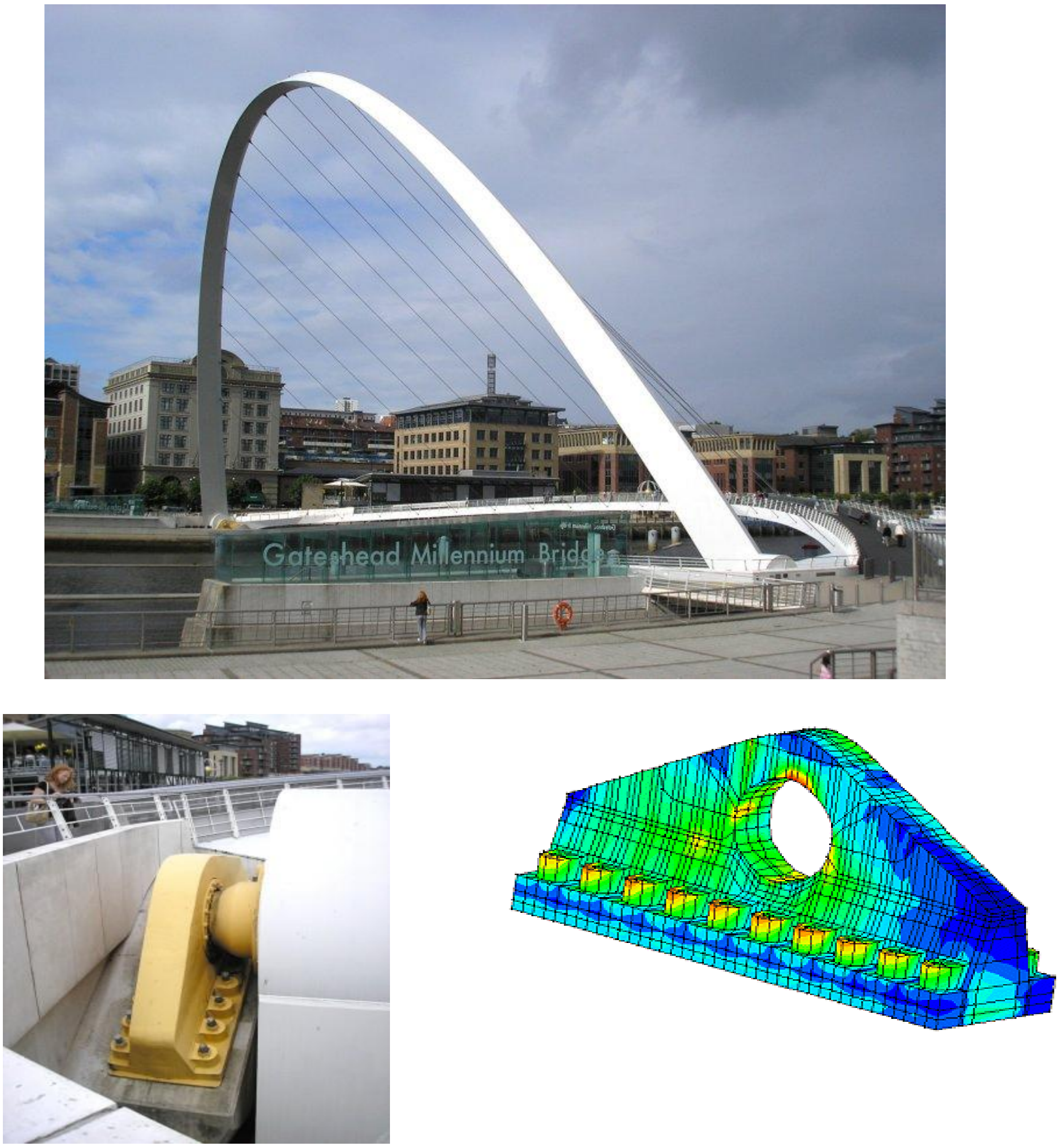



**Fig 14 – Gateshead Milennium bridge bearings**

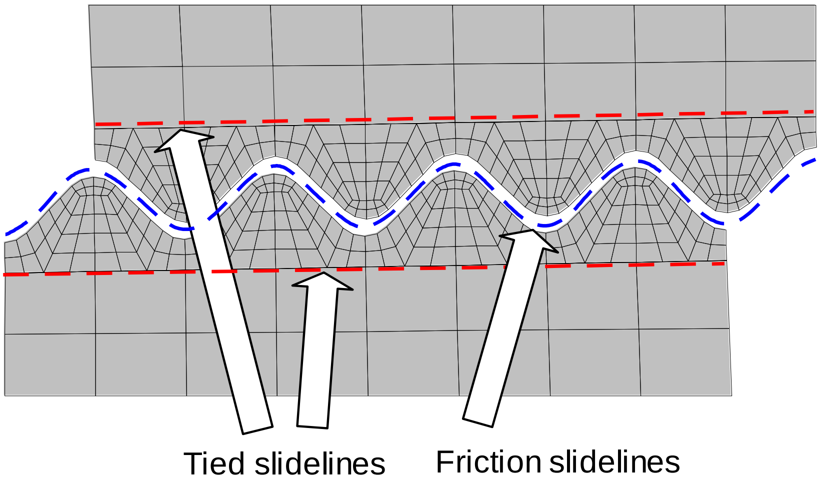



**Fig. 14– Slideline types**

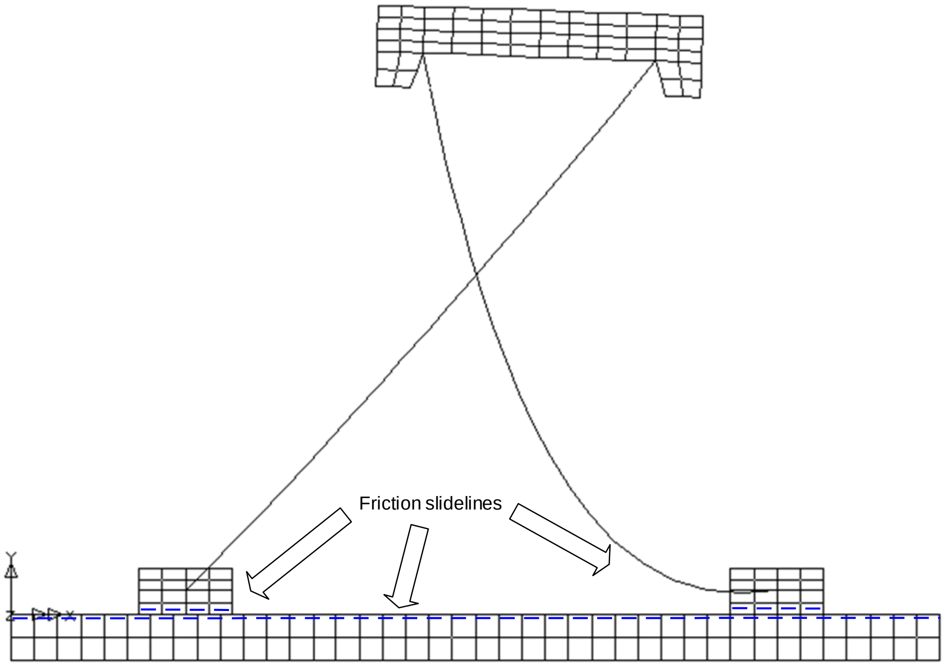



**Fig. 15– Example slideline application**