FINITE ELEMENT ANALYSIS OF JOINTS, BEARINGS AND SEISMIC SYSTEMS

Terry M J Cakebread

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 Honours 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 design and load rating.

ABSTRACT

This paper describes and illustrates how advanced Finite Element Analysis (FEA) software has been used to 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 30 years and become one of the leading FE 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 or friction/pendulum bearings
- It will discuss why dampers and other seismic systems are employed and cover the methods of modeling them.

- It will also show 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 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 want to be able to model and predict with a fair degree of accuracy the response of structures that incorporate increasingly sophisticated joints and bearings to ensure that they articulate properly under a range of static and dynamic 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. To give one example, consider the case of lift-off from a bearing occurring for part of a structure that was ignored in the modeling. A better solution would be to remove the bearing support if the reaction was negative. This would then allow for lift off but this 'solution' would mean that in a subsequent loadcase, if the support took load, it would no longer be there. A better solution in this case would be to use a full nonlinear joint which allows for lift off and re-contact as necessary.

A range of basic and advanced joint models are described in this paper. Modeling of the response of a structure can be done by using global modeling with assigned joint properties. 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

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.

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. They may have 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. 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, coefficient of linear expansion and damping factor. Nonlinear joint models[2] typically provided in finite element software, and as shown in **Fig. 1**, 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.

Seismic Isolators

These more complex joint models exist to control the damage impact of seismic activity on structures. These joint types may be summarised 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. 2**, 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 idealised 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.

Viscous Dampers

Visco-elastic dampers can be modeled using the four parameter solid model shown in **Fig. 3** 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

Halving/Hanger Joints

Halving/hanger joints, as used with drop-in concrete or steel spans, are a fairly simple joint to model in the global sense. The global steel truss bridge model, as shown in **Fig. 4**, incorporates a joint-supported drop-in span. In these cases, normally all that is required is that the joint acts as a support when the load on the joint is downward, then when the load is lifted it allows the bridge to articulate upwards. It can also be used to restrict horizontal movement when it locks up but this is often not modeled. Normally only a check is carried out to ensure that the movement does not exceed the travel allowed for the joint.

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 (see **Fig. 5**) 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[4] 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 modelled the elastomeric bearings and seismic dampers of a 1108m long, multi-span bridge structure in the Mediterranean region, as shown in **Fig. 6**, 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 defined at the respective centroid of each structural component modelled 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 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. 7** 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 LUSAS.

LOCALIZED MODELING OF JOINTS AND BEARINGS

Concrete Deck Half-Joints

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.[5] 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. 8**. 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 where 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 Complex, showing actual capacities were significantly higher than those calculated from the assessment codes and sufficient to sustain the assessment loading.

Deriving Joint Properties For Global Analysis.

When joint properties cannot be easily defined localized joints models may be used to derive suitable modeling values for use in a global seismic analysis, as carried out for the concrete encased riveted steel frame structure of the Cathedral Building in San Francisco[6]. The particular beam /column connections of the structure result in it being classified by FEMA[7] as a "Partially Restrained" moment frame. FEMA-356 does not provide explicit guidance on appropriate moment-rotation properties for the minor axis joints in the transverse direction, where the beams frame into the webs of the columns. With this arrangement, a moment at the end of the beam will impose a twist on the column web before it is transferred to the column flanges. This adds flexibility to the joint and also provides an additional inelastic mechanism (web yield) which can affect the overall response of the joint. In order to determine the nature of this effect, a series of finite element models of typical minor axis joints were developed in LUSAS. Triangular thick shell elements with quadratic formulation were used to construct these models and nonlinearity was incorporated by way of Von-Mises yield criteria. The effect of the concrete encasement in preventing inward movement of the column flanges was incorporated in the model by way of compression-only strut elements. These models were used to determine nonlinear moment-rotation curves representing the isolated effect of web flexibility. The moment-rotation curves were then incorporated in the definition of the overall moment-rotation of the minor axis joints determined using the FEMA procedure.

Beam / Column Moment Connection Research

Research work carried out by Jon Lindsey of HNTB at the University of Kansas into the potential use of alternative moment-resisting connections[8] shows very clearly the benefit in using FE analysis alongside experimental testing. The project's aim was to make design recommendations to allow structural designers to increase the economy of steel moment-resisting frames. Several different configurations of an extended end-plate moment connection were analyzed that typically included wide-flange steel shape sizes intended for use in multi-storey structures in moderate to high seismic zones. Both exterior (one-sided) and interior (two-sided, cruciform) connections, underwent assessment. Loading was applied using displacement-controlled loadcurves - a means of loading each connection model by applying a predefined increasing displacement to the end of the beam member. These displacement parameters were based on prescribed inter-storey drift increments. The singlecycle loadcurve was proportioned such that the model would experience significant yielding at the peak displacements of the cycle. By using nonlinear solid modeling with slideline surface contact (to be explained later in this paper) excellent correlation was achieved between the results predicted by LUSAS and measurements obtained from detailed experimental testing. Stress time history plots, of the type as seen in **Fig. 9,** showed the formation of stress concentration zones and areas of yield. Load versus total displacement (**Fig. 10**) and time history data was graphed to record the correlation of the experimental results.

Collapse Analysis of Bridge Bearings

Even back in 1995 bearings were being analysed using finite element analysis. Then, UK Consultant Hyder 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 FE models assessed the performance of both shell and solid element idealisations. Final all-solid models similar in nature to **Fig. 11** 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.

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 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. 12** 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. 13** 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, as was the case in the beam/column connection and bridge bearing examples described previously, 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. However, comparing predictions made using the range of analytical joint models developed for use by finite element analysis software against measured data is often more difficult, and sometimes this is because the manufacturers of various bearings and dampers are reluctant to put their detailed behavior into the public domain. If manufacturers were to make public relevant data relating to the behavior of their bearings it would particularly help engineers in carrying out structural assessments of existing structures where the articulation and damping properties of such devices may be unknown.

CONCLUSIONS

With the advanced finite element analysis tools available today it is possible to model all different types of joint and bearing conditions. These can be used in conjunction with line beam models when global modeling is carried out or they can be modeled in detail using plane stress or solid localized models. Often, because of the very nature of the problems to be solved it will require nonlinear analysis. Verification of finite element modeling results for a structure against measured or test data is useful when additional modeling is to be carried out. Bearing and damper manufacturers need to give more information to designers to enable them to model the structural systems that use their devices easier.

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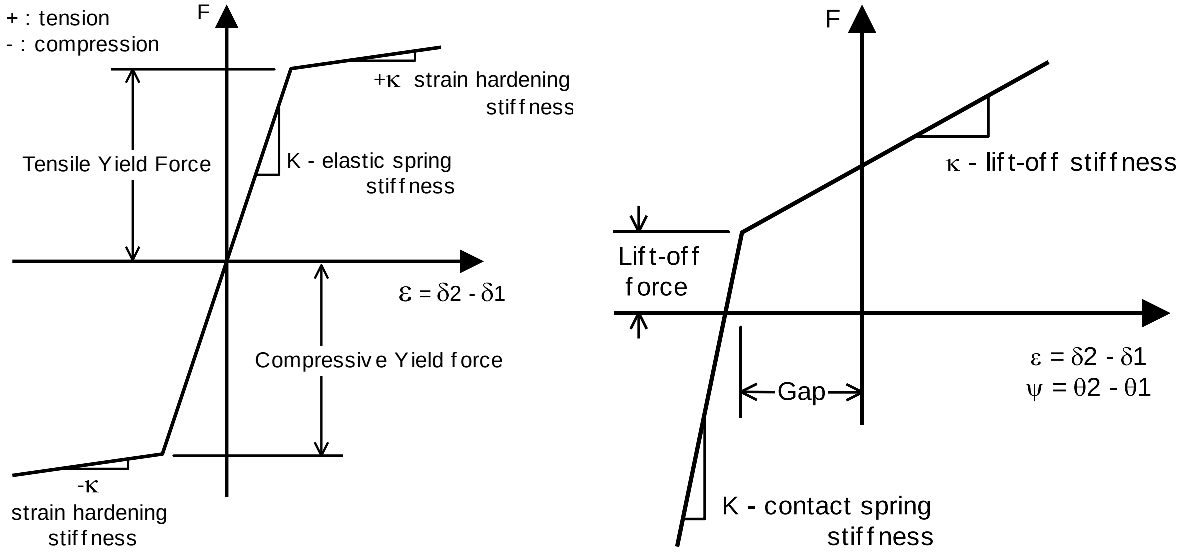
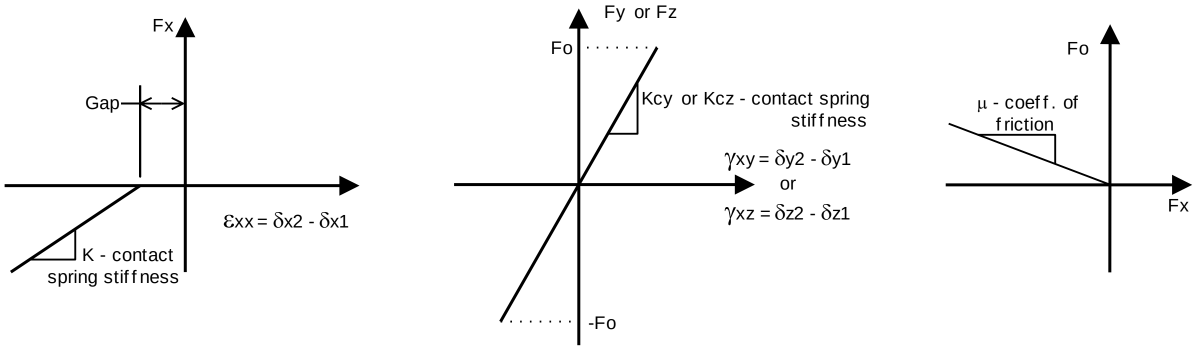


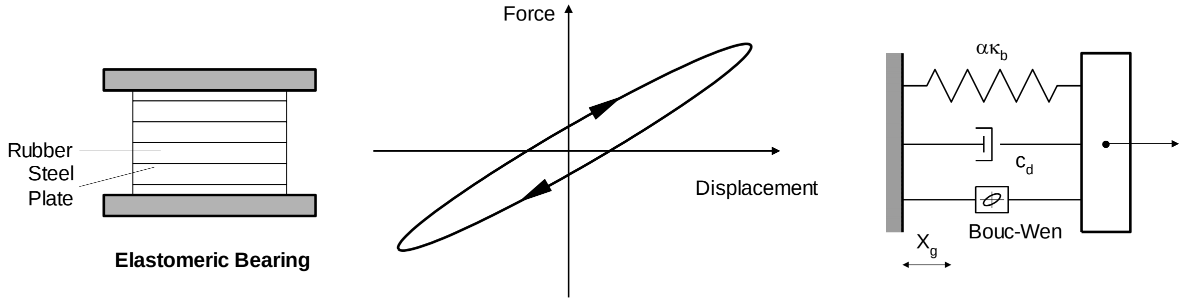
Elasto-plastic

Smooth contact

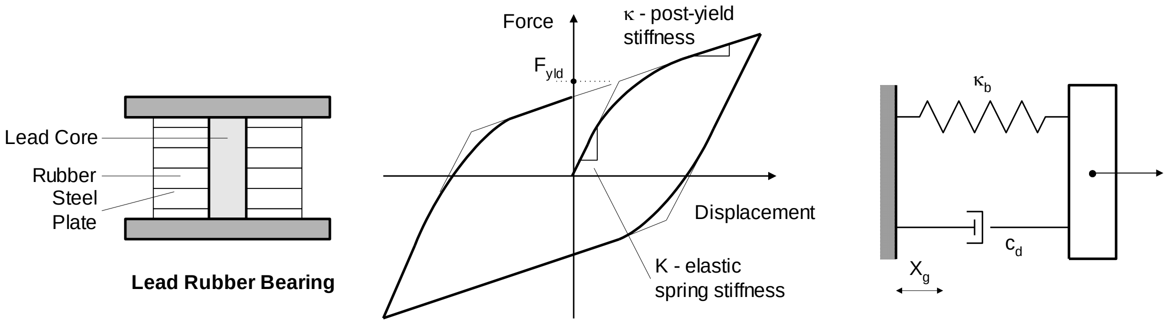


Frictional Contact

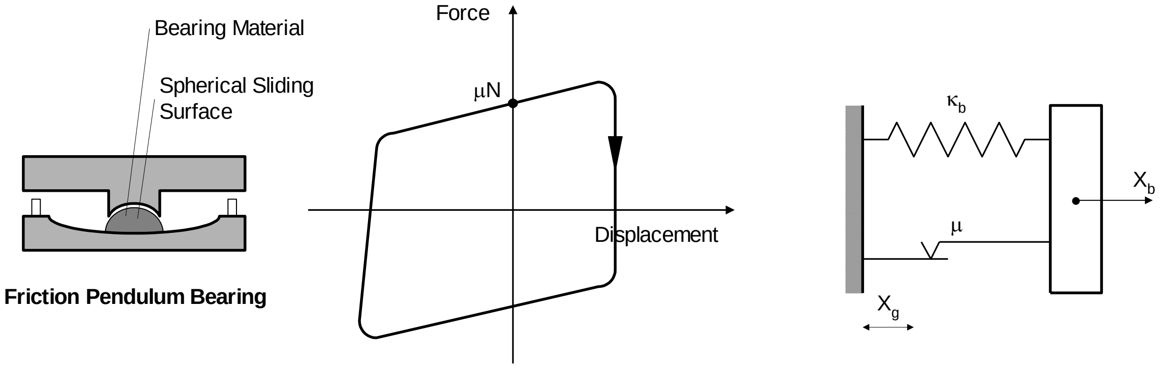
Fig. 1–Elasto-Plastic, Smooth Contact and Frictional Contact Joint Models.



High Damping Rubber Bearing, Hysteretic Behavior and Schematic Representation



Lead Rubber Bearing, Hysteretic Behavior and Schematic Representation



Friction Pendulum Bearing, Hysteretic Behaviour and Schematic Representation

Fig. 2-Seismic Isolator Types

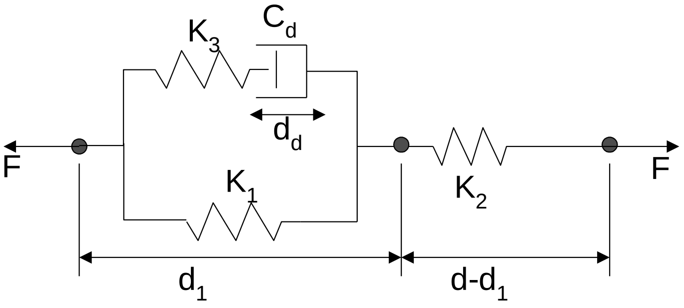


Fig. 3– Four parameter solid model for visco-elastic bearings

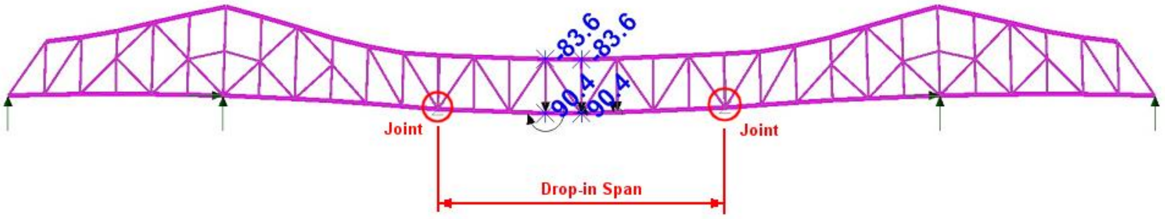


Fig. 4– Truss Bridge with Drop-in Central Span

Fig. 5– Dock Caisson under Construction

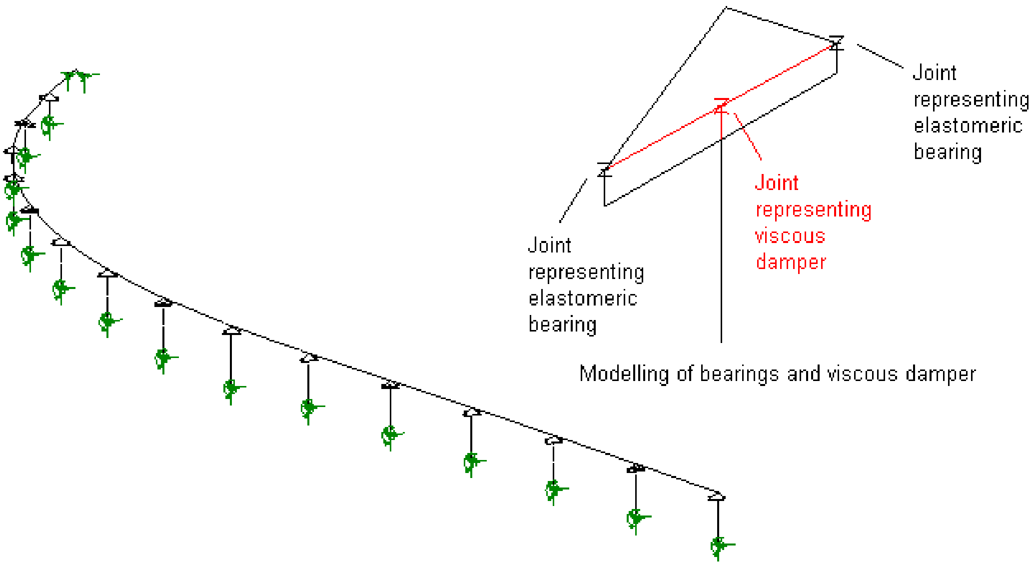
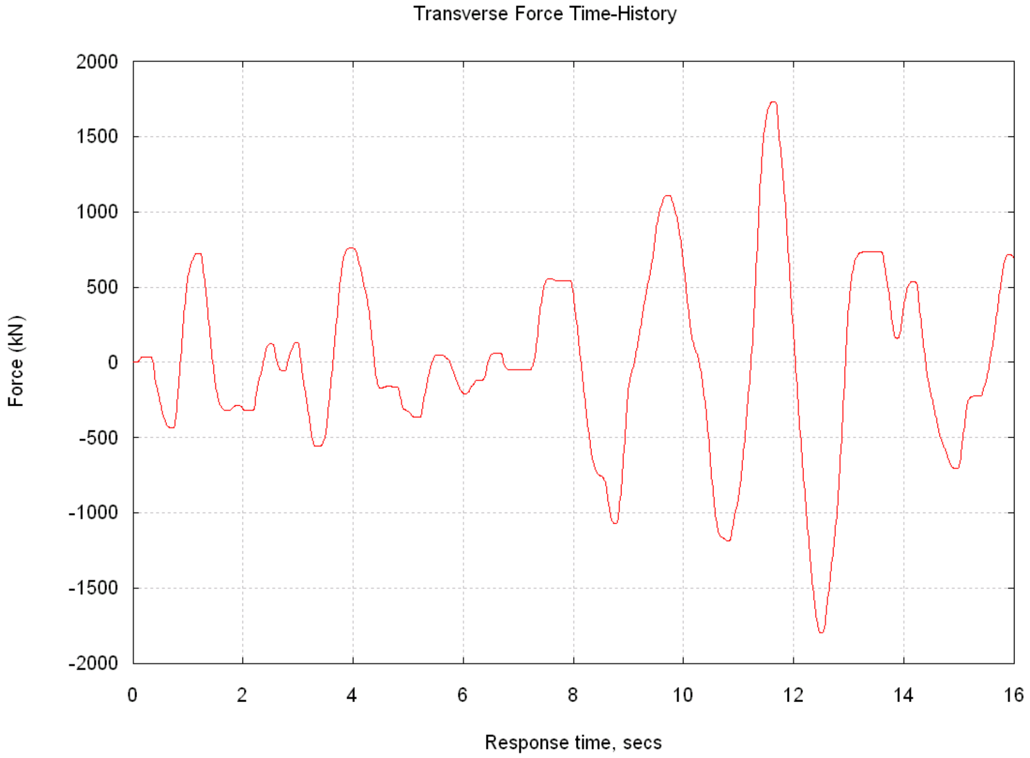


Fig. 6– Global Model of Viscous Damped Road Bridge



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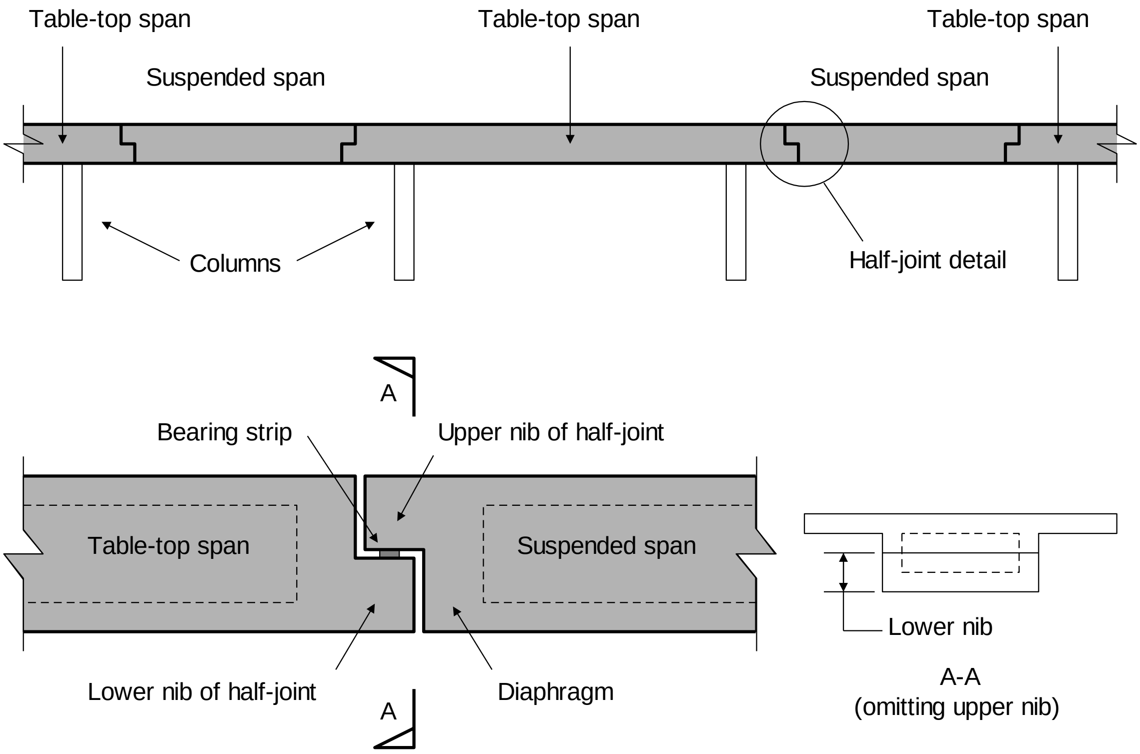


Fig. 8-Schematic Half-joint Geometry for Kingston Bridge Approach Ramps

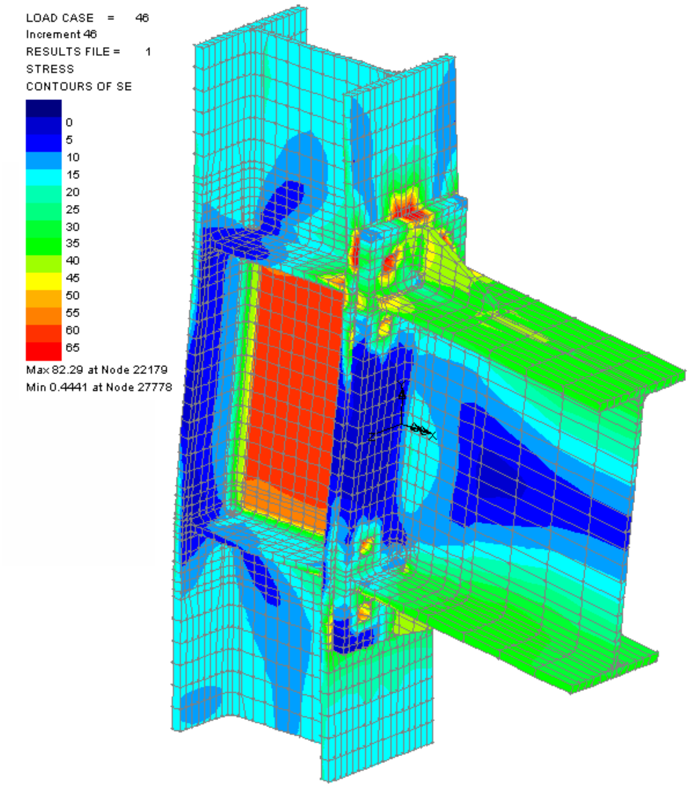
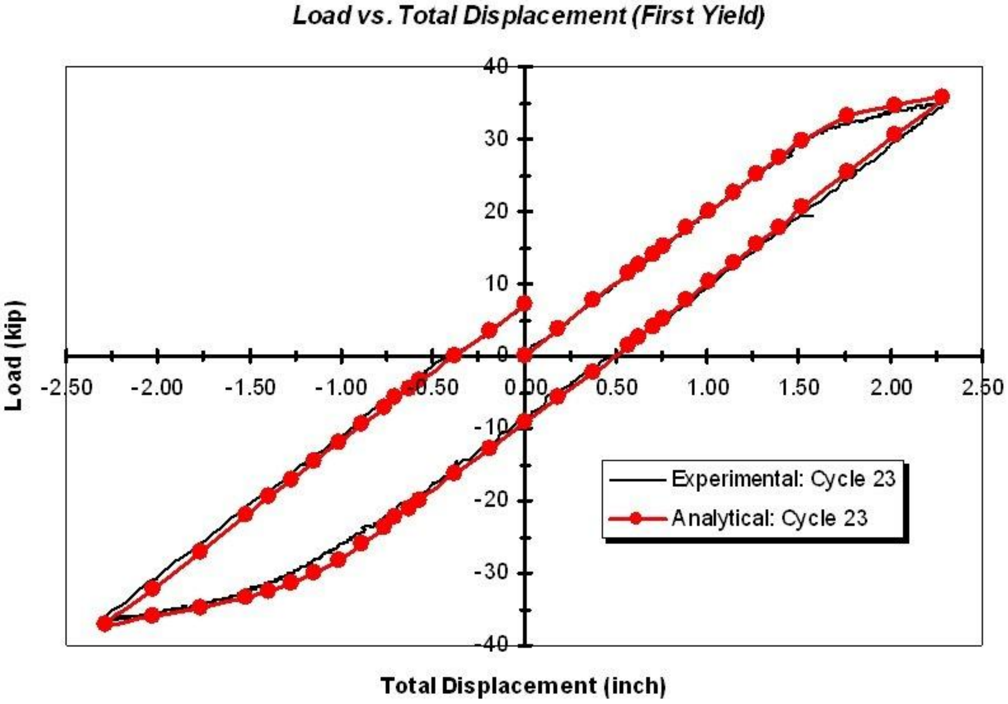


Fig. 9– Stress Concentration Zones in a Bolted Beam / Column Connection



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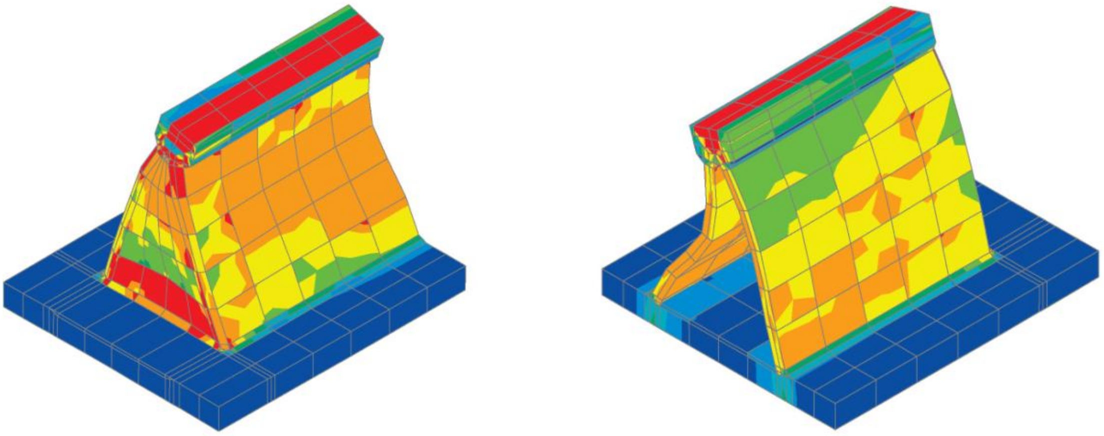

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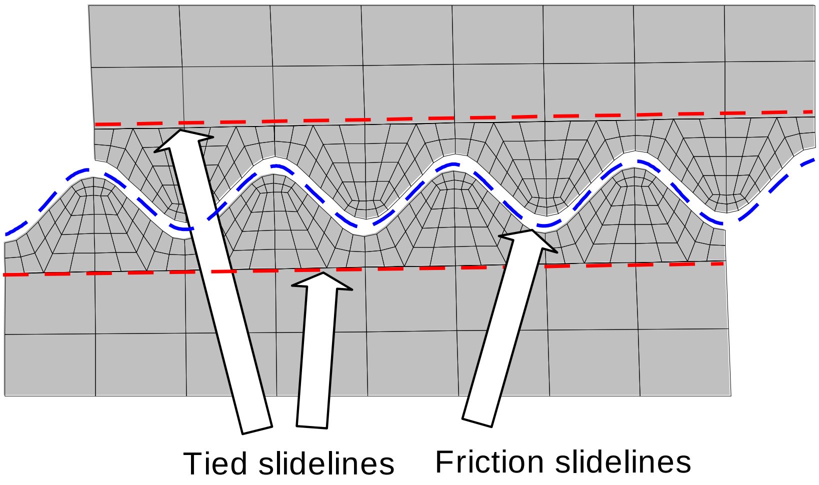

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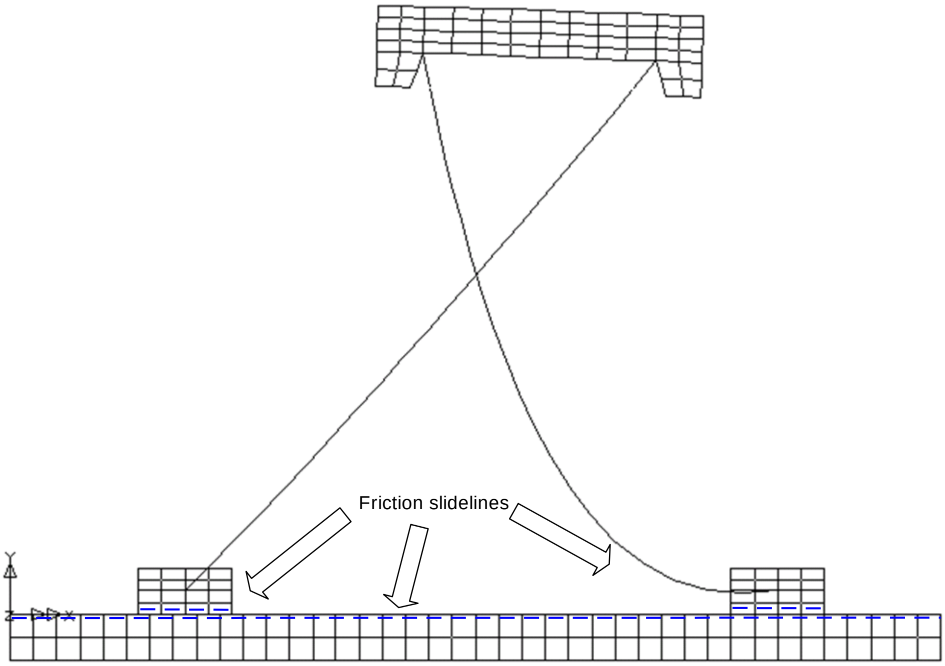

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