THE USE OF FINITE ELEMENT ANALYSIS IN THE DESIGN OF FOOTBRIDGES

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Summary

This paper aims to highlight the benefits of using finite element (FE) analysis for different types of footbridge design and illustrate those benefits with reference to a diverse range of urban regeneration footbridges of various construction materials that are either under construction or have been completed in recent years. It does so with reference to design codes relevant for a structure as built and to the newly introduced Eurocodes. Key analysis tools highlighted include those for calculating member resistances for linear and nonlinear buckling analysis, dynamic analysis capabilities, pedestrian loading, energy dissipation devices and staged construction modelling. The paper concludes that the use of finite element analysis can lead to more efficient, cost-effective footbridge designs and that its use is just as valid for low-cost 'practical' footbridges as it is for the design of more technically advanced and expensive 'iconic' structures.

Keywords: finite, element, analysis, design, footbridge, buckling, dynamic; loading, pedestrian, damping

1. Introduction

Footbridges are increasingly being constructed to act both as landmark structures and as focal points for urban regeneration projects. For the latter, they are often used to re-establish routes that in some cases have been lost when the construction of a new major road or railway has severed the existing connection, or to re-connect a community that has grown up and developed whilst being separated by a river. For both uses the trend towards more architecturally-influenced slender structures has resulted in more detailed and refined analysis often being required to enable these types of structures to efficiently resist their in-service loadings. Finite element analysis is now widely used to help refine and optimize footbridge designs for these described situations, both for straightforward and practical footbridges where relatively low construction cost or speed of erection are of primary concern, as well as for footbridges of impressive architectural and engineering achievement, where construction cost has provided less of a restriction to the end result.

2. Practical footbridges

2.1 Baker Bridge

An excellent example of a practical but eye-catching cable stayed footbridge designed using finite element analysis for rapid erection and for a relatively low overall cost is Baker Bridge in Exeter, UK [1]. Designed by Hyder Consulting Ltd for Exeter Chiefs Rugby Club / Devon County Council, it carries a three metre wide footway/cycleway at an unusually high 12m above carriageway level. A single 42m high, steel A-frame tower supports a front-span of 72m and a back-span of 38m via 4 pairs and 3 pairs of cable stays respectively. The north-side abutment of the shorter back-span is also designed to act as a counterbalance. The legs of the tower are protected against vehicle collision by large concrete bases and feature simple bolted flange joints to speed erection. To construct the bridge a temporary support tower was erected at the midpoint of the longer span and the steel deck units for both spans were assembled sitting simply supported at the supports. Once all were in place the deck units were welded together to create a continuous deck prior to stressing the cables to a predetermined value and an in-situ concrete deck was cast. Hyder used finite element analysis software to assist with its design of the bridge and built a detailed model to mimic all stages of the construction sequence. Beam elements modelled all members apart from the concrete deck where shell elements were used. Because the footbridge provides the main pedestrian access to a rugby stadium the design of the slender deck required a detailed time-step analysis to investigate any potential dynamic effects that could be induced by the passage of large crowds. A pedestrian loading wizard (described later) was used to achieve this. The bridge was completed at a total project cost of £650,000.

Fig. 1 Baker Bridge

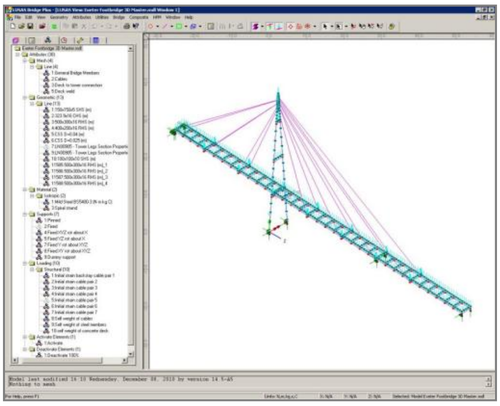


Fig. 2 FE modelling of Baker Bridge

2.2 Itford Farm Bridleway Bridge

An example of the use of finite element analysis in the creation of a low-cost, environmentally sensitive structure is Itford Farm Bridleway Bridge [2]. Designed by InterRoute on behalf of the UK's Highway Agency, it carries walkers, cyclists and horse riders using the South Downs Way National Trail over the busy A26 trunk road. It is composed of three simply supported modified Warren steel truss girders which, for aesthetic and practical reasons, are clad with timber boarding. Pedestrian and particularly horse loading were of interest with respect to the deck plate thickness. 3D FE modelling using beam elements to represent the truss members and thick shell elements to represent the deck plate helped prove the design and a localised detail model investigated potential high shear loads from offset bearings. In this instance an attractive solution was obtained for a total contract value of around £700,000.

Fig. 3 Itford Farm Bridleway Bridge

2.3 Dubai Metro Footbridges

More high-profile, and of steel N-truss design, the 205 footbridges on the 52km long Red and 24km long Green Lines of the Dubai Metro [3] provide 24-hour, air-conditioned access for the general public to enter the elevated stations and also permit the crossing of numerous roads along the route. Atkins used a modular design approach in conjunction with detailed FE analyses of the main footbridge types to enable it to design the large number of footbridges required in the time available. For each footbridge, thick beam elements modelled the primary structural members of the steel truss, crossheads, and concrete pierhead and pier. Piled supports were modelled using the equivalent cantilever method. Joint elements of appropriate stiffness and freedoms represented the articulation of the bearings. Lumped masses, applied throughout the model, and with an appropriate eccentricity, modelled the mass distribution of the cladding and finishes to the roof, walls and floor. From a close inspection of the mass-participation factors, eigenvalues and frequencies obtained from each FE analysis the primary longitudinal, vertical, lateral and torsional modes could be identified. Graphs of total mass participation plotted against frequency showed quite clearly when particular amounts of structural mass became excited for certain frequencies and animations of selected eigenmodes permitted easy visualisation of the true structural response.

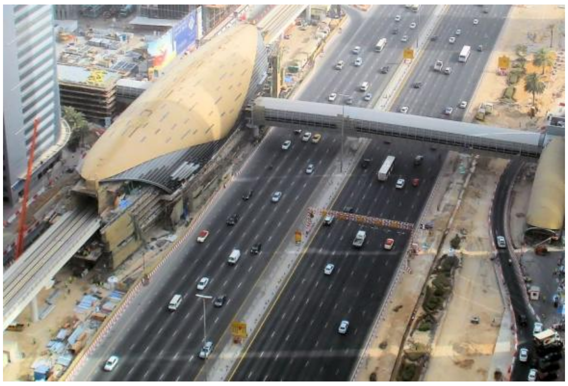


Fig.4 Dubai Metro station and typical access footbridge

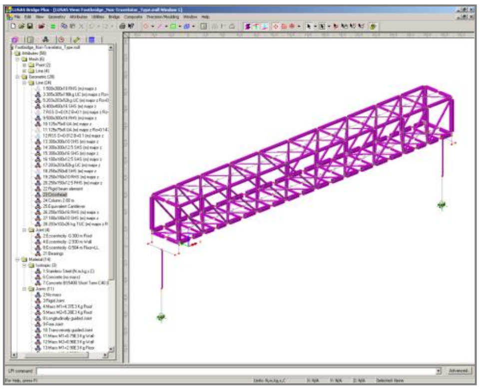


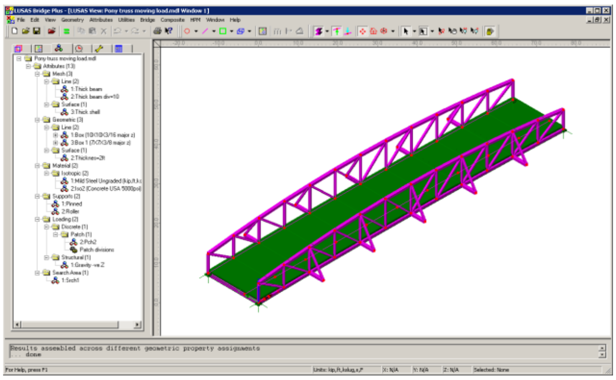
Fig. 5 FE modelling of a Dubai Metro footbridge

3. FE Modelling and Results Viewing

FE software provides numerous modelling, analysis and results viewing tools to assist with the design of all types of footbridges and the key facilities and benefits are described throughout this paper. By way of stating general usage and capabilities, FE software models are typically created using feature-based geometry methods where layers of information and the visibility and properties of each layer can be controlled and accessed independently. Model attributes such as thicknesses, material, loading type etc. are defined and appear in a separate panel listing for assignment to selected geometry of the model using a "drag and drop" technique. Automatic meshing and mesh refinement is often available. Built-in associativity, a key benefit if provided, ensures that if the model geometry is amended, all assigned loadings, supports, assigned mesh and other attributes are automatically updated on the model.

Results viewing options typically include using separate layers for the display of diagram, contour, vector and discrete value data allowing bending moments, shear forces, and deflections to be displayed on deformed or undeformed structural shapes and on fleshed or unfleshed beam sections. Often results can be displayed in global or local directions, in element directions, or at any specified orientation and multiple slices may be cut through 3D solid models on arbitrary planes and results can be selectively output to spreadsheet applications for additional calculation and graphing uses. Animations of mode shapes, or for viewing of structural response to moving loads and seismic events, and for investigating the spread of concrete cracking or yielded material are particularly useful. User-defined results calculation facilities, again if provided, allow model and results parameters to be built into arithmetic expressions giving a spreadsheet-style capability inside the software, and offer an alternative to external results manipulation. Reports can be created from selected modelling, loadcase and results textual and graphics data.

In summary, the animation of a moving load across a bridge deck showing deflections and stresses, or an animation of a cable stayed bridge being constructed in 'real time' both illustrate, very simply, the benefits of using today’s state of the art FE technology.



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Results assembled across different geometric property assignments
... done
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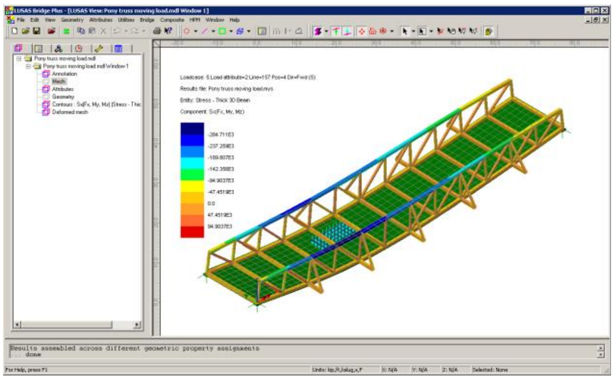
Fig. 6 Simple application of FE modelling.



Loadcase: 5:Load attribute=2 Line=157 Pos=4 Dir=Fwd (5)
Results file: Pony truss moving load.mys
Entity: Stress - Thick 3D Beam
Component: Sx(Fx, My, Mz)

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Results assembled across different geometric property assignments
... done
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Fig. 7 Animation of moving load analysis.

4. Using FE analysis

FE analysis has always required a fundamental understanding of structural behaviour and users of it will always need to know what limitations there are with any particular modelling technique. With FE analysis, it is good practice to carry out a mesh sensitivity check to ensure that results are accurate. Mesh density should be checked to ensure enough elements of the type chosen are being used because coarse mesh patterns could, for some types of analysis, produce unconservative results. Software that allows for mesh patterns to be easily refined and manipulated without losing any assigned supports and loading is most beneficial here. Quadratic elements (if available) generally produce better results than linear elements but a check should generally be made for balanced loads/forces (check reactions and displacements) and boundary conditions on a linear model first before moving on to more advanced analyses. Most importantly, when using FE analysis, engineers need to be using well-supported and tested software so that they can rely on the results and call for assistance when undertaking unfamiliar analysis.

5. Member Resistances and 2nd Order Analysis

For plate girder, box girder or truss footbridge designs etc., linear and nonlinear buckling FE analysis can investigate structural stability during erection, help to optimise the size of web and flange plates, bracing, stiffeners and position of any temporary supports used, or even look at the effects of a slab casting sequence. Using finite element software that permits buckling analyses to be carried out on structures idealised using beams, plates, shells, or solid elements (and any combination of these) is undoubtedly of more use than software that can only handles a limited sub-set. Material nonlinear effects (e.g. yielding or concrete cracking) and boundary nonlinear effects (e.g. lift-off, tension-only members etc.) are also of great use.

Using FE analysis, an elastic critical buckling load can be determined directly from an eigenvalue buckling analysis enabling the calculation of member resistances. The eigenvalue buckling analysis also enables an assessment of the importance of 2nd order effects to be made with respect to codified values and, if deemed to be important, these may be obtained by carrying out a geometrically nonlinear analysis. For the recently introduced Eurocodes an eigenvalue buckling analysis is used in EN1993-1-1 as part of the calculation of member resistances. It is also used to calculate α_{cr} in EN1994-2 clause 5.2.1 (3). If $\alpha_{cr}<10$, a 2nd order analysis will be required.

Where the type of structure isn’t covered by a design code, and where P-delta, lift-off and yielding effects are not significant in the loading range up to buckling, a linear buckling analysis should give a more accurate assessment of member resistance than would be obtained from a code of practice. However, imperfections and nonlinearities tend to prevent most ‘real’ structures from achieving their theoretical elastic (or "Euler") buckling strength, so the eigenvalue buckling load factors are therefore somewhat overestimated.

As an alternative to empirical formulae such as those typically available in design codes, a full nonlinear buckling analysis may be undertaken to get a more accurate answer. With a geometrically nonlinear analysis (where material and boundary nonlinearity can also be investigated if found to be required) the stiffness matrix of the structure is automatically updated between loading increments to incorporate deformations which affect the structural behaviour (this is sometimes described by engineers as P-delta effects). Nonlinear buckling can be performed on the original structure without imperfection, or by automatically adding an imperfection based upon a scaled deformed shape which could be from a linear buckling model. A structure may also experience some material nonlinearity during a buckling event (yielding for example) and/or some boundary nonlinearity (lift-off supports, perhaps). Generally it is recommended that FE modelling of nonlinear effects is done progressively in order to evaluate the results at each stage to help develop an understanding of the structural behaviour and help to identify the cause of any potential failed analyses.

5.1 Redhayes Bridge

Both linear and nonlinear analyses were carried out by consultant Parsons Brinckerhoff on the Redhayes Bridge [4], due for completion in early 2011 and one of the first major highway infrastructure projects designed and constructed to Eurocodes in the UK. This modified tied-arch structure spans 82m across the M5 motorway near Exeter. Geometric nonlinearity investigated the sensitivity of the structure to second order large-displacement effects, and on the basis of these findings, it was established that initial section sizing could be performed using the results of a first order analysis, simplifying the superposition of load effects. Buckling behaviour was investigated accounting for both geometric and material nonlinearity and the modal dynamics established to find the vertical, transverse and twist modes and frequencies. The primary modes were then used for more detailed pedestrian moving-load and steady-state analysis in accordance with the requirements of the UK National Annex to BS EN 1991-2 using a pedestrian loading wizard which is described later in the paper.

Fig. 8 Redhayes Bridge

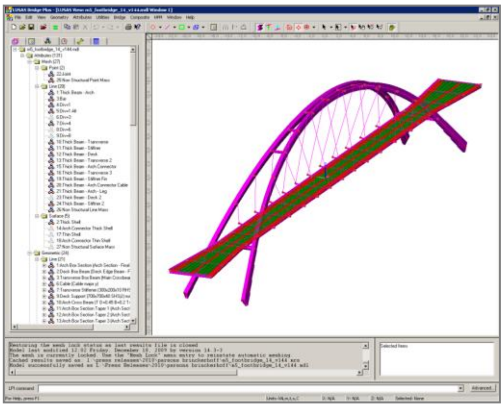

Fig. 9 FE modelling of Redhayes Bridge

5.2 Ponte Della Musica

A competition-winning design for the Ponte della Musica [5], developed up to tender design status by Buro Happold is currently under construction in Rome, Italy The bridge is the first dedicated large scale pedestrian bridge to be built over the River Tiber since Roman times and comprises two leaning steel arches with a clear span of 130m between spring points, that support a steel deck designed for pedestrian usage but with provision for future incorporation of a tramway. A dynamics analysis of the structure for both natural frequency and forced vibration and a nonlinear bucking analysis of the two large arches using output derived under static load combinations, for both trams and buses, and also for large crowd loading helped to optimize the design of the structure.

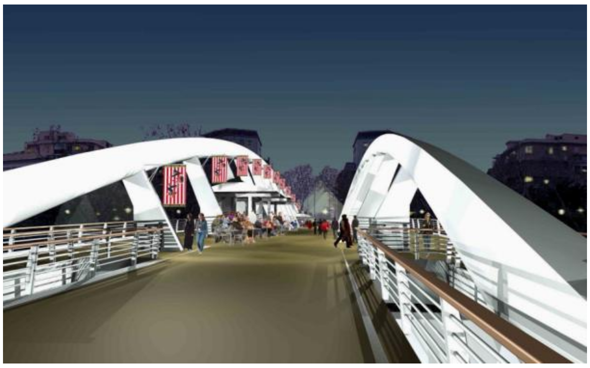

Fig. 10 Ponte della Musica

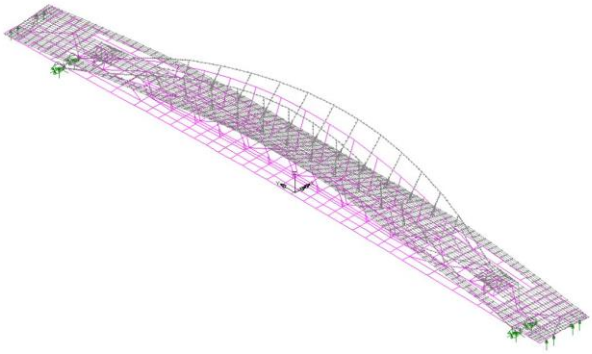

Fig. 11 FE modelling of Ponte della Musica

6. Dynamic analysis

The trend towards more architecturally-influenced slender steel structures has resulted in ever more detailed and refined analysis being required to assess these types of structures. Dynamic analysis of footbridges may require a variety of techniques including those for calculating eigenvalues (natural frequencies); the use of Interactive Modal Dynamics (modal superposition) methods; time domain (full transient); and in extreme cases possibly also implicit (low velocity) and explicit (shock) methods. In addition, nonlinearity including material and geometric nonlinearity with or without contact may need to be considered.

The conversion of a linear static model to a model suitable for dynamic analysis is normally a straightforward one, simply requiring the definition of loading, a time step and an optional damping value. A transient dynamic analysis (sometimes referred to as a step-by-step analysis) is carried out when loading may not reasonably be considered to be instantaneous, or where inertia or damping forces are to be considered. The solution is progressed through time in a step-by-step manner by assuming some variation of the displacements and velocities over small intervals of time. Within each time step the solution yields the displacements at the discrete time points representing the end of the current time step. For known initial conditions, successive application of this procedure provides the dynamic response of a structure.

For the UK the introduction of the Eurocodes has seen a move from design codes implying that computer modelling may be used to derive particular parameters to a more prescriptive statement stating that it should be used for certain situations. The standard Eurocode 1: Part 2, which defines models of traffic loads for the design of road bridges, footbridges and railway bridges states that, depending on the dynamic characteristics of the structure, the relevant natural frequencies of the main structure of the bridge deck should be assessed from '*an appropriate structural model*.' Pedestrian loads are, however, left to the designer. Whilst dynamic models of pedestrian loads and associated comfort criteria may be defined in the National Annex or for the individual project, the analysis of these loading groups and types is best handled by FE modelling.

6.1 Dynamic Modelling of Pedestrian Actions

In the UK National Annex to EN1991-2, pedestrian comfort checks for serviceability should be carried out if the fundamental frequency of the deck is less than 5Hz for vertical vibrations and 2.5Hz for torsional vibrations. It is further required that accelerations in the bridge deck do not exceed specified design limits of 0.7 vertically and 0.2 horizontally for normal use, and 0.4 for exceptional crowded conditions. To evaluate the response of a structure to pedestrian loading a number of FE tools/analysis methods are available:

- An eigenvalue frequency analysis permits simple checks to be made and forms the basis for rigorous checks
- Interactive modal dynamics (a modal superposition method) provides a good assessment of response and is also useful for seismic assessment to EN1998
- Transient (step-by-step) dynamics provides a fully flexible solution for all dynamic analysis problems
- A pedestrian loading wizard can create the necessary moving and varying-magnitude load, based on input such as the recommended Bridge class (NA to EN1991-2, Table NA.7).
- Crowded conditions (which require time-varying UDLs), groups of joggers and larger groups of people walking must be modelled dynamically.

Models that are used to determine natural frequencies for the simple criterion in EN1990 clause A2.4.3.2(2) can generally be easily updated to include dynamic actions. Nonlinear behaviour (such as tensioning-stiffening behaviour associated with the use of cables) can also be incorporated when necessary.

In one FE system, LUSAS [6], a pedestrian load wizard provides the means to apply vertical oscillating pedestrian loading to a bridge model in accordance with the UK national annex to BS EN 1991-2 2003. It simplifies and automates the creation of the numerous loadcases required to correctly model the passage of pedestrian groups across a structure. After first carrying out an eigen analysis to derive the key fundamental mode shapes and frequencies, a dynamic analysis is then undertaken to model the behaviour of the structure to a moving and pulsating pedestrian load. The specification of Bridge classes (A, B, C or D) and Pedestrian types (walking or joging/running) control the reference load and speed of the moving pulsating load representing the pedestrian or pedestrian group. Based on the selection of bridge class and pedestrian type the recommended group size from Table 7 of the UK National Annex is set. The vertical natural frequency governs the frequency of the pulsating pedestrian load and it is also required for the determination of the Pedestrian Combined factor from Figure 8 of the UK National Annex to deal with the effects of a more realistic pedestrian population, the harmonic responses and the relative weighting of pedestrian sensitivity to response. An unsynchronized reduction factor which is dependent upon both the effective span and structural damping is obtained from Figure 9 of the UK National Annex. The direction of pedestrian movement and the time step /incremental distance for each stage of the analysis can be controlled. After running a dynamic analysis, results can be viewed as animations, contours of peak accelerations, and graphs can be readily created to investigate the acceleration / time response for any location on the structure. Then, if structural response is found to be excessive some amount of re-design may be required or the introduction of energy dissipation devices will need to be considered.

6.2 Energy Dissipation Devices

Energy dissipation devices such as mass and viscous dampers are often designed into footbridges or added as part of a retrofit to provide protection against vandalism or from unwanted natural effects. Tuned mass dampers (TMD) help to stabilize structures against violent motion caused by harmonic vibration and balance the vibration of a system with a comparatively lightweight component so that the worst-case vibrations are less intense. In doing so, the frequencies and amplitudes of the TMD and of the structure should ideally match each other so that each time the structure moves, the TMD creates an equal and opposite 'push'. A TMD comprising a mass (m), a spring (k), and a damping device (c) is typically modelled as a single joint element having those particular properties. Viscous dampers provide structural protection against damage due to seismic events (or other induced excitations) and are designed to ensure optimum energy dissipation over a wide range of velocities resulting in the mobilisation of an almost constant reactive force during a seismic event. They require strategic placement on a structure for best effect and can dramatically reduce induced motion, give smaller structural displacements and restrict "g" forces. To model this, a viscous damper joint model should be specified along with detailed damping data that should be obtained from the unit's manufacturer. For a structure that includes either tuned mass dampers or viscous dampers an eigenvalue analysis is first carried out to arrive at a natural frequency for the first vertical mode. Then a transient dynamic analysis is carried out applying the point loads as a harmonic oscillation with a frequency to match that of the mode of interest.

6.3 Pilsen Footbridge

On the Pilsen Footbridge [7], a cable stayed footbridge that spans around 65m across the D5 motorway near the town of Plzen in the Czech Republic, finite element analysis and dynamic loading tests showed that the structure was very susceptible to pedestrian loading, and especially by vandalism, meaning that an energy dissipation device needed to be installed. Two models of the footbridge, one without a tuned mass damper, and one with, were created to assist with the calculation of TMD parameters. From an FE analysis natural frequencies and mode shapes for the structure were obtained and the first two modes in the vertical direction were found to be within a specified problematic range. As a result a pedestrian loading assessment was carried out based on a draft copy of EN1991-2 which involved three pedestrian loading situations: a group of pedestrians modelled by a pulsating single force; a constant stream of pedestrians modelled by a pulsating constant uniform load; vandalism where a group of ten people are effectively jumping up and down together at problematic frequencies. For pedestrian comfort, and in addition to having to meet specified displacement criteria, an acceleration comfort value of less than $0.7 m/s^2$ had to be met. From FE modelling and analyses of the three pedestrian loading types it was seen that this value was greatly exceeded by the group of pedestrian loading ($1.8 m/s^2$), let alone a moving stream of people ($11 m/s^2$), so the installation of a tuned mass damper was chosen as the best solution to reduce the structural response. Dynamic response of the structure was investigated using the modal superposition method involving step-by-step analysis. Following the installation of the TMD the same dynamic pedestrian loading as used on an initial in situ test was carried out on the footbridge. Measurements showed that, with the TMD fitted and for the critical case of deliberate vandalism, the acceleration in the deck was reduced to just one-tenth of its previous value.

Fig. 12 Pilsen Footbridge

Fig. 13 Glass Bridge

6.4 Glass Bridge

The 15m diameter spiral ramp of the Glass Bridge in Coventry, UK [8], is a good example of a complex torsion structure that has been fitted with tuned mass dampers. Whilst it forms only 50m of the bridges total length of 130m, it is the main engineering feature and like the rest of the bridge is formed of a simple 762mm diameter steel tube that is pre-bent to the various radii needed to form the profile of the bridge. Tubular steel columns, irregularly positioned to avoid features beneath the bridge, support the tube and its intricate steel deck and balustrade system. Consultants Ramboll used FE modelling to investigate the response of the structure and in particular to ascertain the modes of vibration for the 40m long unsupported length of the spiral section. This resulted in three tuned mass dampers, sized to deal with the first principal mode of vibration, being installed within the steel tube to prevent any potential excitation of the structure by vandals.

7. Staged Construction Modelling (Execution Analysis)

For some footbridge designs, and for cable stayed footbridges in particular, accurate modelling and understanding of the staged construction process is particularly important – both at the design stage and at the construction stage where erection manuals for use by contractors are often prepared with reference to FE models and associated results.

Staged construction modelling provides the means to model the step-by-step construction or partial disassembly of a structure over time and to evaluate the effects of structural changes, load applications, the addition or removal of supports and, if required, time-dependent material changes. With some FE software, only one model file need be created and this can contain all of the information required to carry out an analysis of every stage of construction and the effects of geometric and material nonlinearity, and time-dependent material effects such as creep and shrinkage can all be included within the one analysis run. With a model of the completed structure created either a backward (deconstruction) analysis could be carried out (which cannot take account of locked-in stresses or time dependent effects) or a forward (construction) analysis can be done where most of the structure is initially deactivated before elements are re-activated in sequence. Changes to the stiffness of members (and the other staged construction actions such as changes to support conditions etc) require updating of the stiffness matrix between stages. Therefore a staged construction analysis is classed as “nonlinear” and might also include other nonlinear behaviours, such as material yielding, P-delta effects or lift-off. Sliding bearings may be modelled using nonlinear contact (involving what are commonly called slidelines) and support and loading facilities can include temporary/traveller loads. Loads can normally be applied anywhere on a model and loading/stress/strain can be specified to change over time and stresses can be locked-in, if applicable, between construction stages. Prescribed displacements or jacking loads may be used as spans are completed.

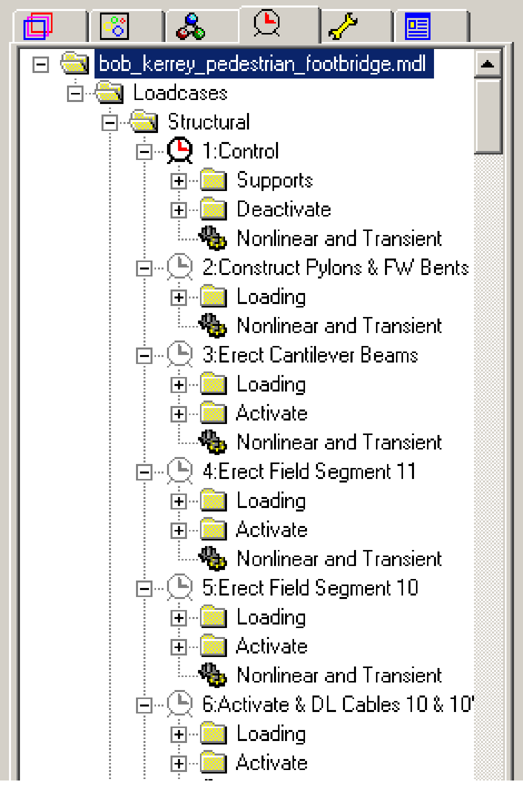

Fig. 14 Typical Loadcase Treeview

The complete staged construction analysis process for a model is typically controlled in what is called a loadcase Treeview. When modelling, groups of structural elements and associated attributes can be activated and deactivated to accurately represent each stage of construction. A typical loadcase Treeview showing the initial stages of constructing a cable stayed bridge model is shown.

For concrete structures, time-dependent material properties should include stress related concrete creep and shrinkage to design codes and include creep recovery. Custom time-dependent curves for particular material properties and codes should also be permitted. Prestressing wizards can assist with the definition and assignment of tendon properties and time-stage properties to a model and provide the means to define values for steel relaxation, time effect on elastic modulus, tendon post-tensioning losses from creep, shrinkage, and superimposed loads. Cumulative effects can be reported separately for each loadcase, such as post-tensioning effects, or for the effects of just creep and shrinkage. Incremental effects can also be specified allowing the viewing and assessment of net changes to the structure since the previous stage.

7.1 Erection Engineering

Erection engineering, as typified by that carried out by US consultant Genesis Structures on behalf of numerous contractors, is a key use of staged construction analysis. On the HNTB-designed Wichita Riverfront Footbridges [9] - two cable stayed post-tensioned bridges spanning the Arkansas and Little Arkansas rivers in the USA - Genesis carried out numerous detailed 3D linear and nonlinear FE analyses to analyze the staged erection process and prepare the erection manuals on behalf of the contractor Dondlinger & Sons Construction Co., Inc. Using FE modelling, cable tensioning was optimized giving a reduction in the contractor's build time. The analysis modelled the complex erection sequence involving falsework construction in the river, post-tensioning of the pre-cast concrete deck system, and sequential cable tensioning to lift the structure from its temporary supports to create the free-spanning cable-stayed spans. Project specifications required that the bridge geometry be set-up at the beginning of its service life to obtain the target geometry after 10 years of service. To accomplish this, time-dependent effects due to creep and shrinkage in the post-tensioned concrete deck segments had to be evaluated by using a CEB-FIP 1990 creep and shrinkage material model.

After tower erection each of the 9.7m long deck box segments were constructed upon structural steel falsework supports and initially post-tensioned together for continuity using four, 25mm diameter post-tensioning bars. Following the complete longitudinal assembly of the segments, four 19 strand, 15mm diameter tendons were installed and tensioned to obtain the required compression in the deck system prior to cable installation. A post-tensioning modelling wizard was used to model the erection of the deck segments at each stage of the construction.

Preliminary tensioning of the stay cables in the FE model was accomplished through initial strain loading of the nonlinear beam elements representing each cable. During the actual stay-cable installation, the longitudinal concrete deck system was to be lifted from its temporary supports through a carefully planned installation sequence. The falsework system was required to allow longitudinal movement and shortening of the deck system as well as unrestrained lift-off from the supports. Modelling for these effects was accomplished through the use of nonlinear joint element supports in the FE model. Final tensioning of the stay cables was achieved by applying a negative temperature load to each cable pair to obtain the desire tension. Good correlation was obtained between the tension values predicted by the FE modelling and on-site measurements.

Fig. 15 Wichita Footbridge

Fig 16 Bob Kerrey Pedestrian Bridge

On the HNTB-designed Bob Kerrey Pedestrian Bridge, a horizontally curved, cable-stayed structure with a 154m (506 foot) main span and two, 77m back spans, the bridge constructor, APAC-Kansas, also retained Genesis Structures for its erection engineering experience. The total bridge length including approaches is about 700m - one of the longest for its type in the world and, at the time of its construction, the longest footbridge to connect two U.S. states. From the steel-topped pylons two planes of cables fan out to support a steel framed bridge deck which meanders from one side of the first pylon to the opposite side of the second pylon in an aesthetic “S” shape. Following pylon construction the erection of the superstructure was carried out using the balanced cantilever method to minimize the falsework design. A parallel sequential erection analysis of the cable-stayed spans of the pedestrian bridge helped to verify fabrication geometry and cable lengths and greatly assisted the contractor in the erection of the bridge.

8. Concluding remarks

Once used only by a select few, and sometimes perceived to be difficult to use, finite element analysis has evolved enormously over the years to become easier to use and more widely used as a result. Its use has always required a fundamental understanding of structural behaviour and those that use it will always need to be aware of any limitations that there are with any particular modelling technique. Finite element analysis can help to optimise structural member sizes for applied loadings and lead to more efficient, cost-effective footbridge designs being constructed. Whilst architecturally-influenced slender ‘iconic’ footbridge designs undoubtedly benefit from the more detailed and refined analysis that FE modelling gives, the use of FE modelling and analysis techniques can be applied just as well to simpler, more straightforward ‘practical’ structures.

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