Advanced Bridge Analysis and Design Methods Simplified

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SYNOPSIS
Advanced bridge analysis and design methods have been simplified with the aid of modern bridge software. This paper provides a summary of these new analysis and design methods and the advantages that can be achieved. Topics covered include automated vehicle load pattern generation methods to the new Australian Bridge Code (AS5100) and the New Zealand Transit Manual, recent developments in composite analysis methods for bridges, and the integration of analysis and design procedures.

Automated loading methods use influence surfaces which are a powerful tool for generating vehicle load patterns in accordance with the provisions of the various bridge codes. Complex load patterns can be generated to a high level of accuracy for any desired load effect in both two dimensional and three dimensional bridge models using the influence surface method. The theoretical background and application of this method are presented.

Composite analysis methods have recently been developed such that advanced 3D models incorporating finite elements can be analysed to produce “composite member” load effects. In the example provided in this paper, finite element analysis results from a 3D finite element of a box girder can be easily converted to useful “overall” design effects such as longitudinal bending, torsion, and web shear. This greatly expands the application of finite element models for analysis of complex structures.

Integrated analysis and design technique involves the provision of links between section – beam – analysis – and automated bridge loading procedures. This means that section properties, vehicle positions, analysis results, and design and code checking calculations can be linked together under the one seamless interface. The advantages of this integration are presented.

The above topics are discussed in detail in relation to their implementation of the current release of SAM Integrated Bridge Design software.

1 INTRODUCTION

Recent developments in modern bridge analysis and design software are discussed in the sections following. Three new techniques for bridge analysis and design presented in this paper are as follows:

- Automated vehicle load generation (to the AS5100 Australian Bridge Code and New Zealand Transit Manual);
- Composite analysis methods; and
- Integration of the bridge analysis and design processes.

2 AUTOMATED VEHICLE LOAD GENERATION BY INFLUENCE METHOD

2.1 General

The concept of "Influence Surfaces" is described in detail in Section 2.2. These influence surfaces are used as the basis of the calculation of worst case vehicle load positions for any desired effect to a particular bridge design code.

Figure 2.1 illustrates a graphical representation of a typical influence surface for hogging over the pier that is used for the automation of the worst case vehicle load pattern.

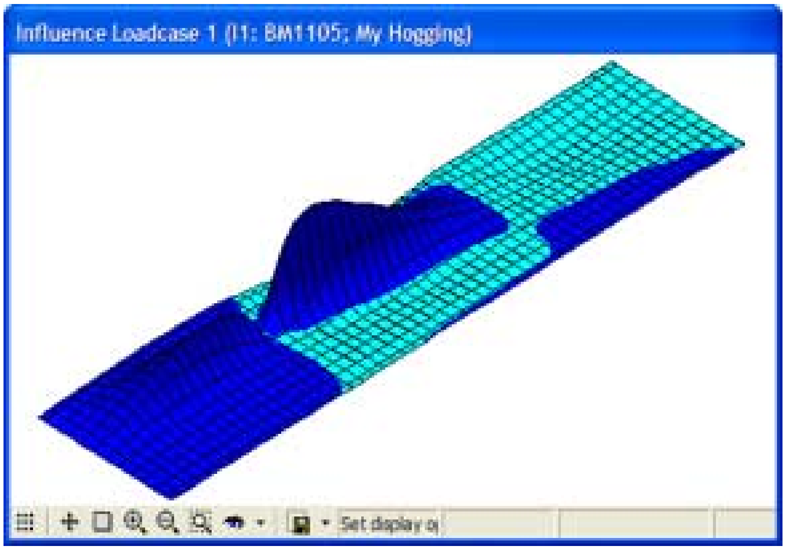

Figure 2.1 – Typical Influence Surface

Figure 2.2 illustrates the corresponding vehicle load pattern that is generated during the automated loading process - in this case being M1600 vehicle loading pattern to AS5100.

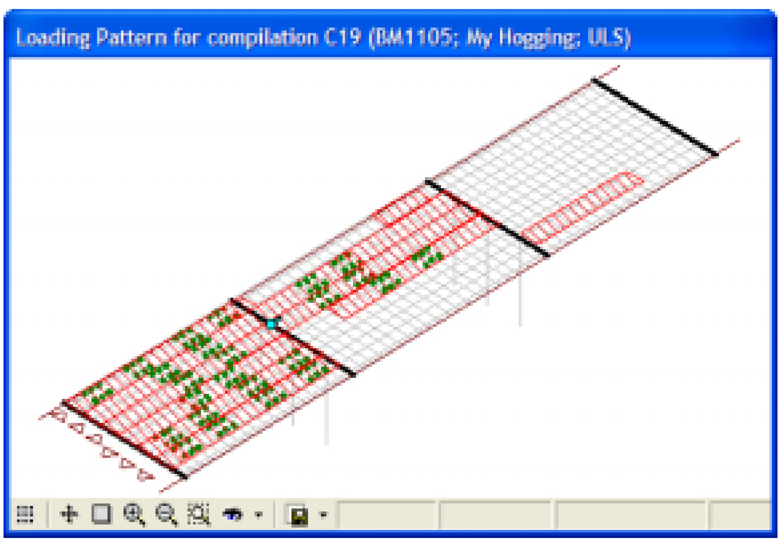

Figure 2.2 - Automated Loading Pattern to AS5100

2.2 Influence Surfaces

Influence surfaces are a powerful tool for bridge engineers in establishing worst case vehicle load combinations. An influence surface relates the value of a load effect at a given point in the structure to the position of a unit point load anywhere on that structure. An influence line is a 2-dimensional form of the 3-dimensional surface, and may be considered as a section through the influence surface or an influence surface for a line beam.

Maxwell's reciprocal theorem (1) states:

> *The deflection at point A due to the application of a load at point B is the same as the deflection at point B due to the application of the same load at Point A.*

In addition, the Muller Breslau theorem (2) states:

> *The deflection at a point A due to a unit distortion at that point is equal in magnitude to the force or moment at point A due to a unit point load applied at the point.*

Combining these theorems it is clear that if a unit distortion is applied to a point anywhere on a structure, the resulting displaced shape is the influence diagram for that point for the force or moment in the direction of the applied distortion.

This can be proven for not only single span beams but also multiple span beams. This theorem also covers rotations and moments. An influence surface can also be generated by applying a point load at a number of positions, and calculating the effects arising from those loads. This forms the surface. However, use of the reciprocal theorem can make influence surface generation simpler and quicker for the engineer. A single distortion can be applied, and the entire surface can be calculated from that one distortion.

For structure models containing finite elements the reciprocal method based on a single distortion load cannot be applied, due to the fact that the solution for finite elements is not fully rigorous. SAM allows the generation of influence surfaces for finite element models using the "direct method". This method applies unit loads to each node in the model, and produces the influence surface by looking at the appropriate results at a given node for each unit load case. This method requires the solution of one load case for each deck joint, and can therefore take much longer to solve than the reciprocal method. SAM allows two "direct method" solution options. The "Direct (Defined)" option outputs results for each of the defined influence surface loadcase locations. The "Direct (All)" option outputs results for all joint and member locations. The latter option allows additional influence surface loadcases to be defined without requiring re analysis, but the analysis will take much longer than the "Direct (Defined)" method.

Once generated, the engineer can then use the influence surface to calculate the loading pattern with the worst effect. This also includes "out of plane" effects such as bending in the web of a box girder modeled in finite elements for example.

2.3 Influence Surface Grids

If the design line is straight then the SAM influence surface loader uses a rectangular influence surface grid. Lane loading can be derived directly by working along one group or ordinates of that grid.

Some programs create influence lines with ordinates as chainages from a datum point. But for curved decks the actual distances between chainages are shorter on the inside of a curve; so load intensities are underestimated if simple chainages are used. SAM creates two sets of grids; one ('rectangular') with points at fixed northings and eastings and the other ('curved') with points at chainages and offsets. The rectangular grid is used to calculate effects of wheel loading (each wheel being calculated at coordinates derived by applying a simple transform to the wheel geometry). The curved grid is used to calculate lane loads; the ordinates in one direction being at constant offsets from the design line and the ordinates in the other direction being perpendicular to the design line. Two grids can take a while to derive (especially the curved grid), so the influence surface loader runs faster for roadways with straight design lines. A typical example is illustrated in Figure 2.3.

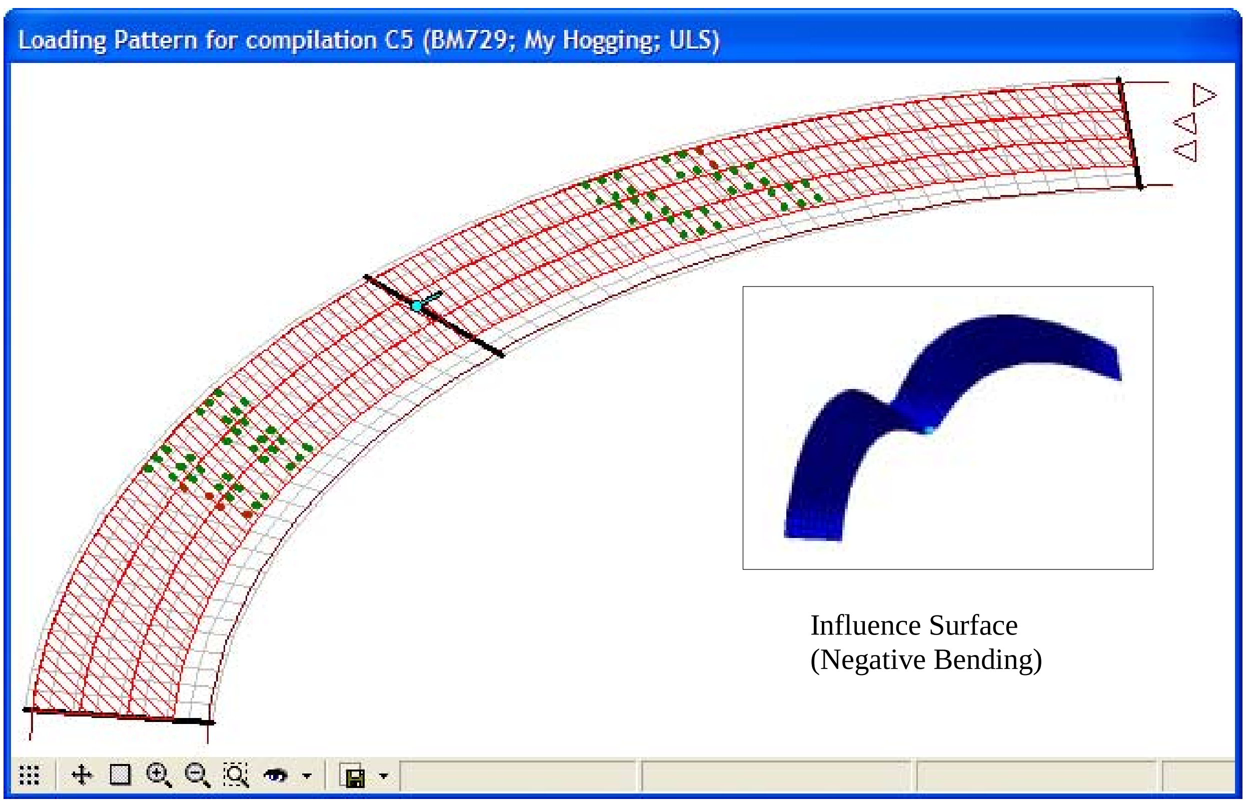

Figure 2.3 Curved Deck M1600 Load Pattern Generated by SAM Automated Loading Method

2.4 Influence Surface Loader

SAM Integrated Bridge Software now carries out automated loading using influence surfaces to the following bridge standards:

- Australian Bridge Code AS5100 (Draft);
- New Zealand Transit Manual;
- British Standards;
- AASHTO LRFD 2;
- AASHTO Standard 17th Edition.

The influence surface loader uses the influence surface technique to calculate critical loading patterns. In general, an influence surface is generated for a particular detail on a structure. This is used to produce the critical loading pattern according to the chosen standard. The most adverse load compilations generated by the influence surface loader are automatically transferred to SAM for analysis to produce results for the critical loading pattern.

In producing the critical load patterns an enormous number of possible load combinations must be checked based on the requirements of the loading code. This involves a large range of loading variables including the following:

- Positioning and comparison of various vehicle types allowed by the loading code;
- Application of any associated lane loading in adverse areas of the influence surface;
- Allowance for variable vehicle axle spacing;
- Adjustment of the transverse design lane position;
- Application of the lane reduction factors;
- Factoring and comparison at ultimate and serviceability limit states;
- Allowance for any variable dynamic load allowance;
- “Special Vehicle” comparisons; etc.

Accordingly, when optimizing for the maximum load effect pattern there is a tremendous amount of storage of data, as loads and combinations are tried, saved, or discarded.

2.5 Australian Bridge Code AS5100 (Draft) Influence Surface Loader

Worst case loading patterns to the Australian Bridge Code AS5100 (Draft) are able to be generated using the SAM Influence Surface Loader. Loading patterns generated to this code are particularly suited to computer aided automation due to the following complications:

- M1600 and S1600 Vehicles are non symmetrical and the position within the span is difficult to accurately predict;
- M1600 and S1600 vehicles can split into two bogies being difficult to accurately position for multi span bridges;

- The uniformly distributed component of the M1600 and S1600 loading is continuous or discontinuous and of any length as may be necessary to produce the most adverse effect;
- Lateral positioning of each 3.2m design lane is varied to produce the most adverse effect;
- Accompanying lane factors vary depending on the order of influence;
- The dynamic load allowance varies for each loading type.

The control screen for the SAM AS5100 Influence Surface Loading is illustrated in Figure 2.4:

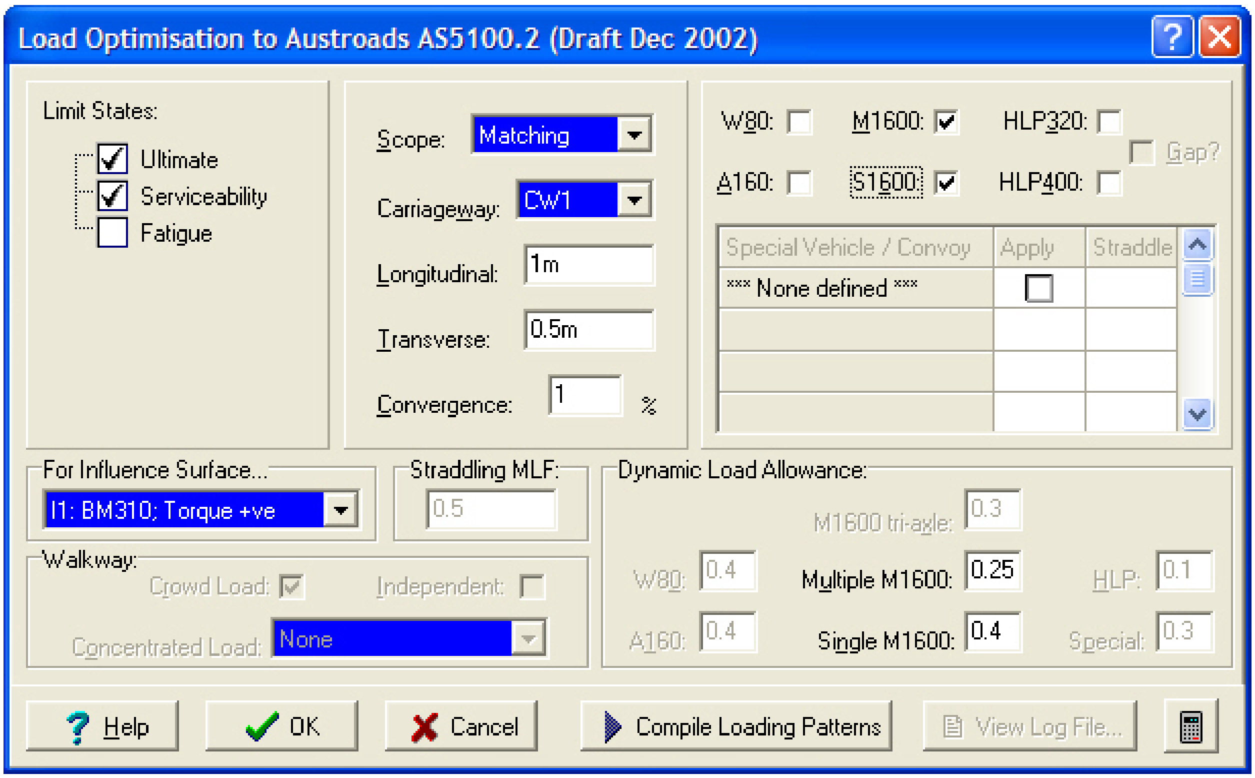

Figure 2.4 – AS5100 Load Optimisation Screen

The AS5100 Influence Surface Loading Module in SAM Integrated Bridge Software automates the production of worst case load combinations and envelopes. This includes the comparison of vehicle types (e.g. M1600 vs S1600 vs A160 axle), allowance for transverse offsets of the design lane, inclusion of the associated UDL loads in positive influence areas only, inclusion of the appropriate associated lane factors and dynamic load allowances, limit state factoring, and compilation and enveloping for multiple effects.

2.6 New Zealand Standards (NZ Transit Manual) Influence Surface Loader

The NZ Transit Manual implementation of the SAM Influence Surface Loader has recently been released. Loading patterns generated to the manual allow for the following:

- Comparison of both HN (Normal) and HO (Overload) loading types;
- The uniformly distributed component of the HN and HO loading is continuous or discontinuous and of any length as may be necessary to produce the most adverse effect;
- Lateral positioning of each 3.0m design lane is varied eccentrically within the load lane to produce the most adverse effect;
- Allowance for Lane Reduction Factors catered for;
- Impact Factor calculated based on either user defined or a specified span length;
- Allowance for HN loading on the kerb is catered for;
- Complete sets of combination load cases are produced in accordance with NZ Transit Manual requirements.

The control screen for the NZ Transit Manual Influence Surface Loading is illustrated in Figure 2.5:

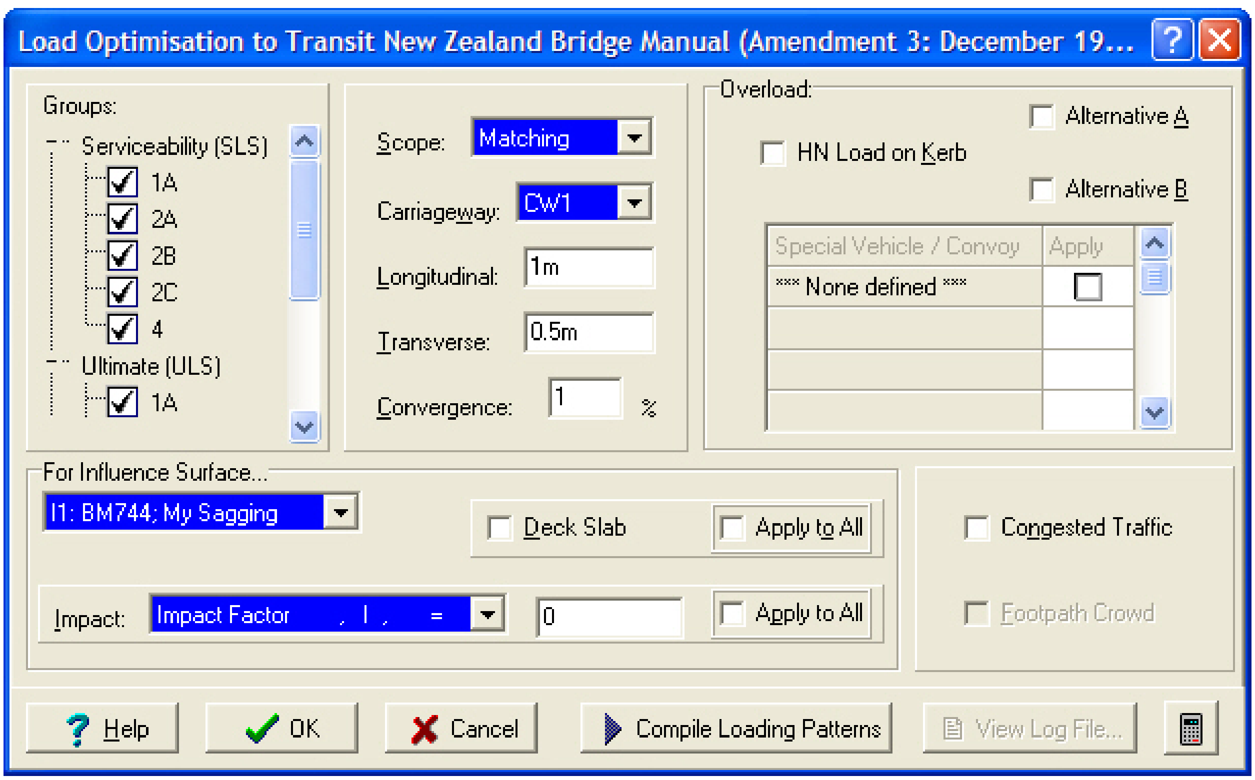

Figure 2.5 – New Zealand Transit Manual Load Optimisation Screen

3 COMPOSITE ANALYSIS METHOD

3.1 Application of Composite Analysis Methods

Composite analysis methods are used in a variety of applications to simplify the interpretation of bridge modeling results. Advanced analysis methods involving the use of 3-dimensional finite elements are a useful way to model the true behavior of a bridge. However, the results are generally difficult to interpret.

For example, the bending effects need to be combined with the membrane forces in eccentric elements to produce an “overall” load effect. A good example of this is the case of a 3D finite element model for a box girder bridge. This model is particularly useful for establishing the transverse effects in the bridge, except that to produce the “overall” bending moment in the box the membrane forces in the top and bottom flange need to be summated around the neutral axis.

Typical finite element results and the corresponding composite member effects are illustrated in Figure 3.1 and 3.2.

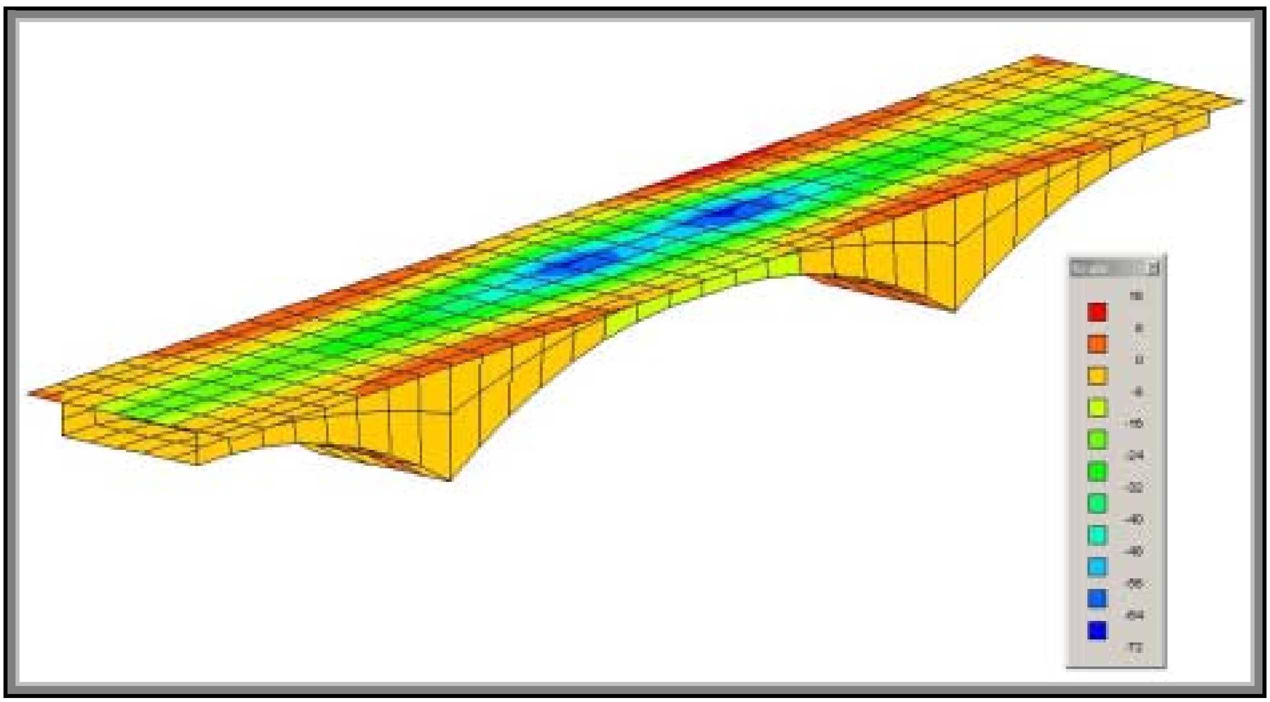

Figure 3.1 – Box Girder Finite Element Model

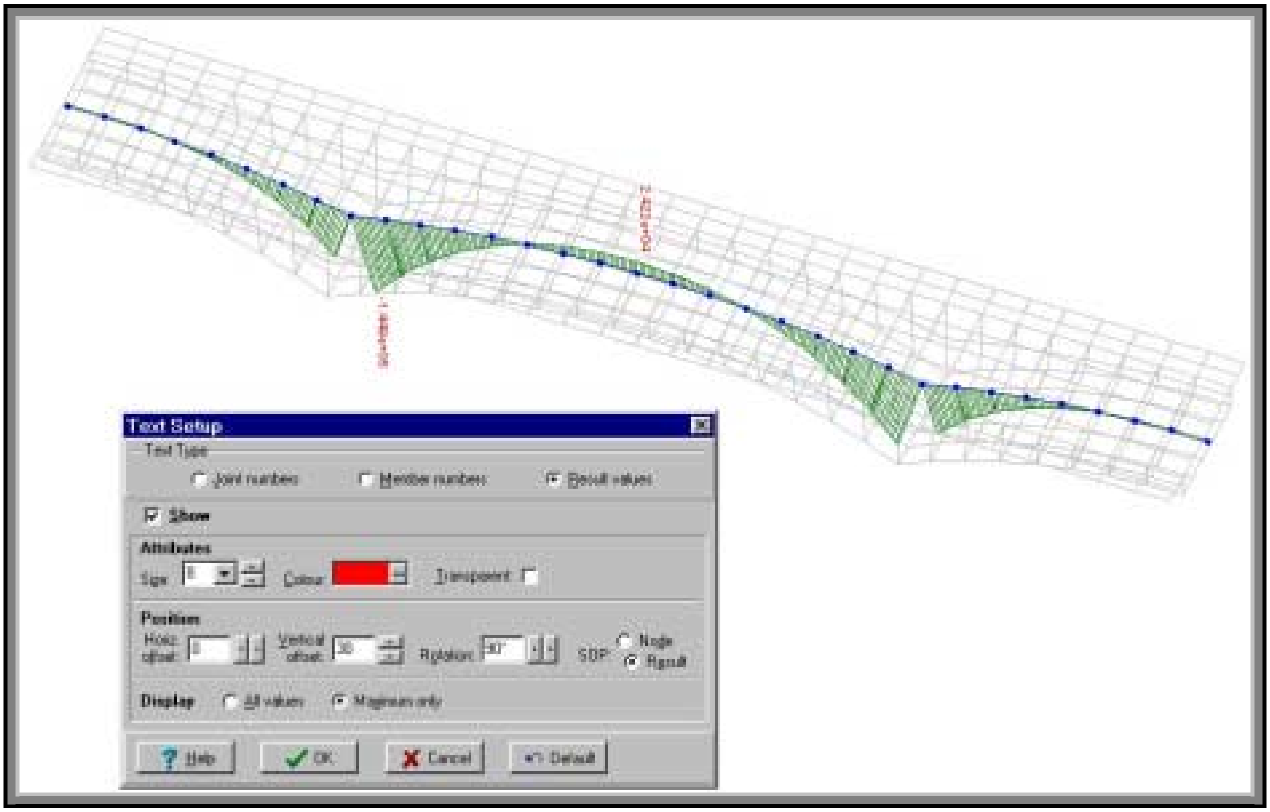

Figure 3.2 – Composite Member Results

The composite analysis methods used in SAM Integrated Bridge Software automate this process by producing load effects associated with a "composite member" definition. A composite member is a combination of beam members and/or finite elements for which a single set of results effects is required at any given section. This method can be applied in a number of applications providing a powerful tool for solving complex bridge load conditions.

3.2 Composite Member Definition

Composite members can be generated in two distinct ways.

1. Explicit definition of each composite member which covers all general types of structure;
2. Automatic generation using the beam modules which can be used in beam/slab type structures.

In the first method, two stages are required for composite member definition. The first defines the beam members and finite elements that comprise the composite member. The second stage defines the composite member axis, which is a series of points at which the composite effects are calculated. Effectively a plane is constructed which is perpendicular to the composite axis, and all the composite member components that intersect this plane have their effects resolved to a single composite effect. The composite member axis also defines the composite member local axes system, according to the same convention as beam elements.

In the second method, a basic grid of plate finite elements is generated in the normal way and then beams, which have been defined in the beam modules, can be assigned to alternate rows of finite element edges. This automatically generates the following:

1. Additional beam elements representing the girder;
2. Section and material properties for the girders;
3. Section and material properties for the finite element slab;
4. Rigid offsets representing the eccentricity between the slab and the girder;
5. A series of composite members representing each beam. The composite axis which should be at the composite centroid is also generated, taking into consideration any specification of cracked concrete over supports.

This method is extremely powerful when the steel girders are tapered or where the bottom flange is curved in a circular or parabolic profile.

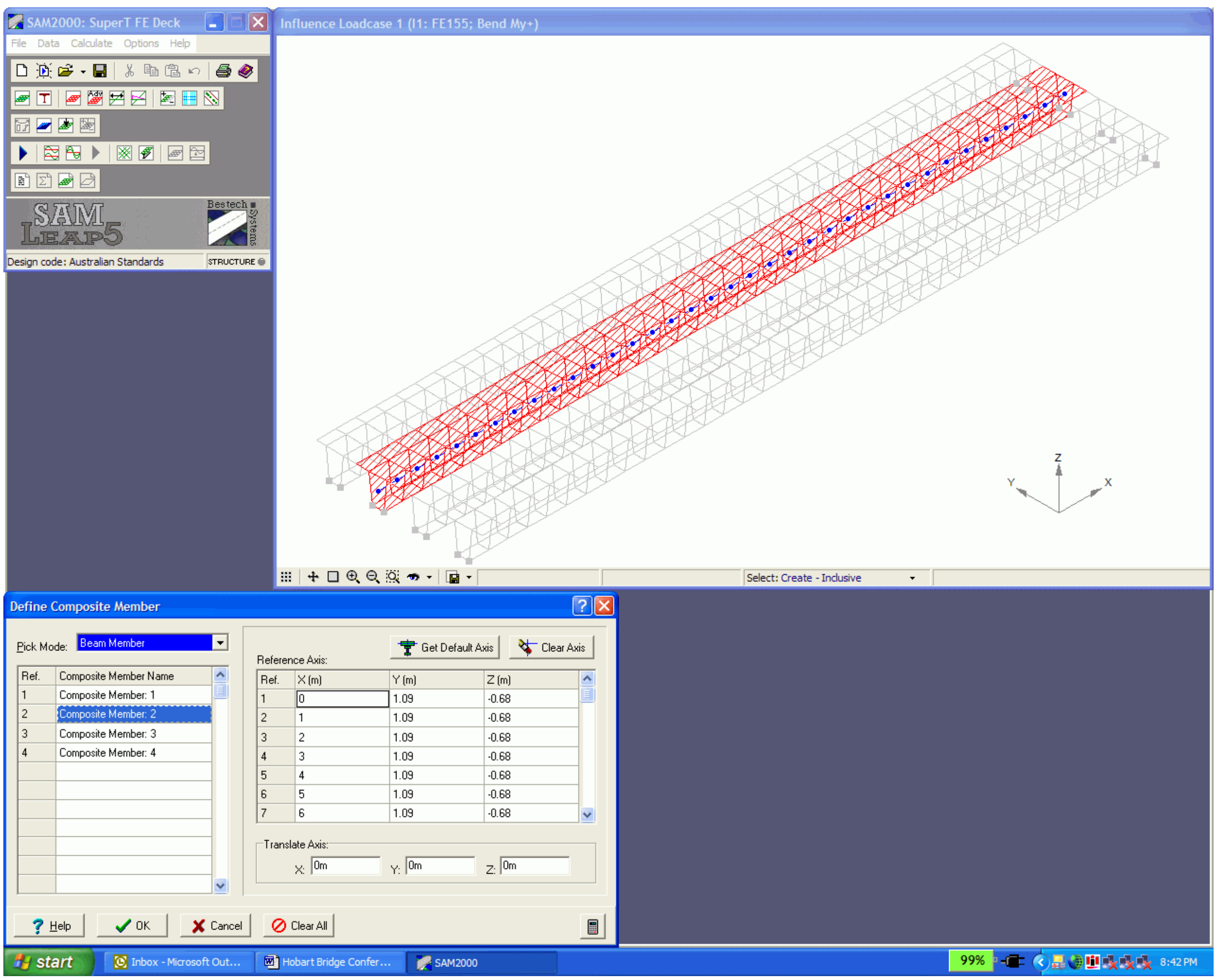

Figure 3.3 - Super-T Deck Modelled in Finite Elements with Composite Member Definition

It should be noted that the inclusion of highly skewed elements in composite member definitions may degrade the accuracy of results.

For composite members that comprise finite elements only, SAM looks at the footprint of the composite member elements in the X-Y plane, constructs a box around this and takes an axis that bisects the box in line with its longer edge. A point along the axis will be generated at each location where the edge of a component element intersects the axis.

For composite members that comprise beam members only, or beam members and finite elements, the program finds a beam or element edge in the Z plane of the default axis, and constructs the axis from all beams or element edges that are in the same plane and are co-linear.

Figure 3.3 illustrated a typical composite member definition for a finite element Super-T deck model.

3.3 Composite Member Results

Figure 3.4 illustrates composite member bending moments for a Super-T precast concrete beam deck modeled in finite elements.

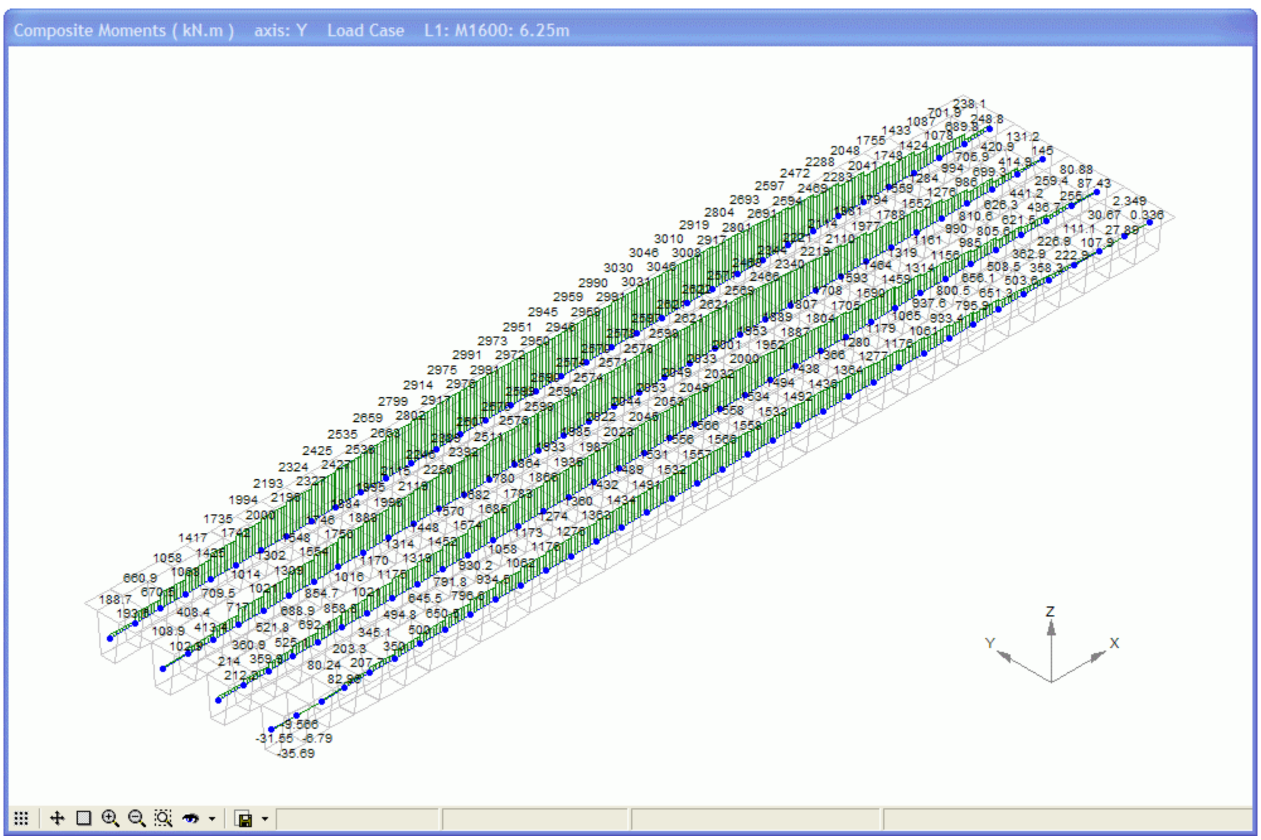

Figure 3.4 - Composite Member Bending Moments – SuperT Deck Modelled in Finite Elements

It should be noted that this model is particularly useful for transverse design of the deck as it can provide a true representation of the transverse stiffness and the span for local wheel effects between the webs and global bending. The models however are more difficult to generate and take longer to analyse than conventional “grillage” or 3D frame models.

3.4 Influence Surfaces for Composite Members

The reciprocal method for generating influences is very efficient for beams and grillages where the designer is interested in the primary components of force, moment and displacement. Sometimes the criteria for design can be defined as a combination of factored primary components. For example: Consider a composite steel/concrete deck, analysed using plate finite elements for the slab and beam elements for the steel girders. We would define a series of composite members as described above to obtain the combine effects of the slab and girder acting together. We would probably be concerned with designing for maximum moments and forces, at ultimate limit state, which will of course be the envelope of composite results.

We would therefore require an influence diagram for composite moments and forces to enable load optimization to be carried out to obtain the maximum effects. This cannot be achieved using the reciprocal method for generating influences as we cannot use distortion loads in finite elements. SAM therefore uses the direct method by applying a unit point load at each node in the deck, solving these load cases, and calculating the composite results, at the desired location, for each load case. The result for each load case represents the ordinate of influence at the loaded point for that load case. The graphical collection of these results will form the influence surface.

In SAM, this procedure can be carried out for any of the six components of composite force/moment. In addition, if the beam modules have been used to automatically generate the composite finite element / beam structure, as described above, then the composite results may be enveloped and seamlessly transferred back to the beam module for design.

4 INTEGRATION OF BRIDGE ANALYSIS AND DESIGN PROCESS

“Integrated Bridge Design” is a technique in which the two major numerical processes in bridge design are brought together. This means that the process of code checking structural components (“Design”) and the process of analysing the structure for moments and shears (“Analysis”) communicate in a very structured way. This leads to great increases in productivity for bridge designers saving them both time and effort.

The concept is simple: any program that designs a beam has full knowledge of all the beam’s self weight and member properties, and just needs tables of moments and shears to become useful. Equally, any program that analyses bridge structures needs section properties to be useful. The integration is achieved by designing the program with a seamless interface such that section property data is transferred from the design program, and moment and shear results are interface back from the analysis program to the design program ready for code checking.

The integration process is illustrated graphically in Figure 4.1

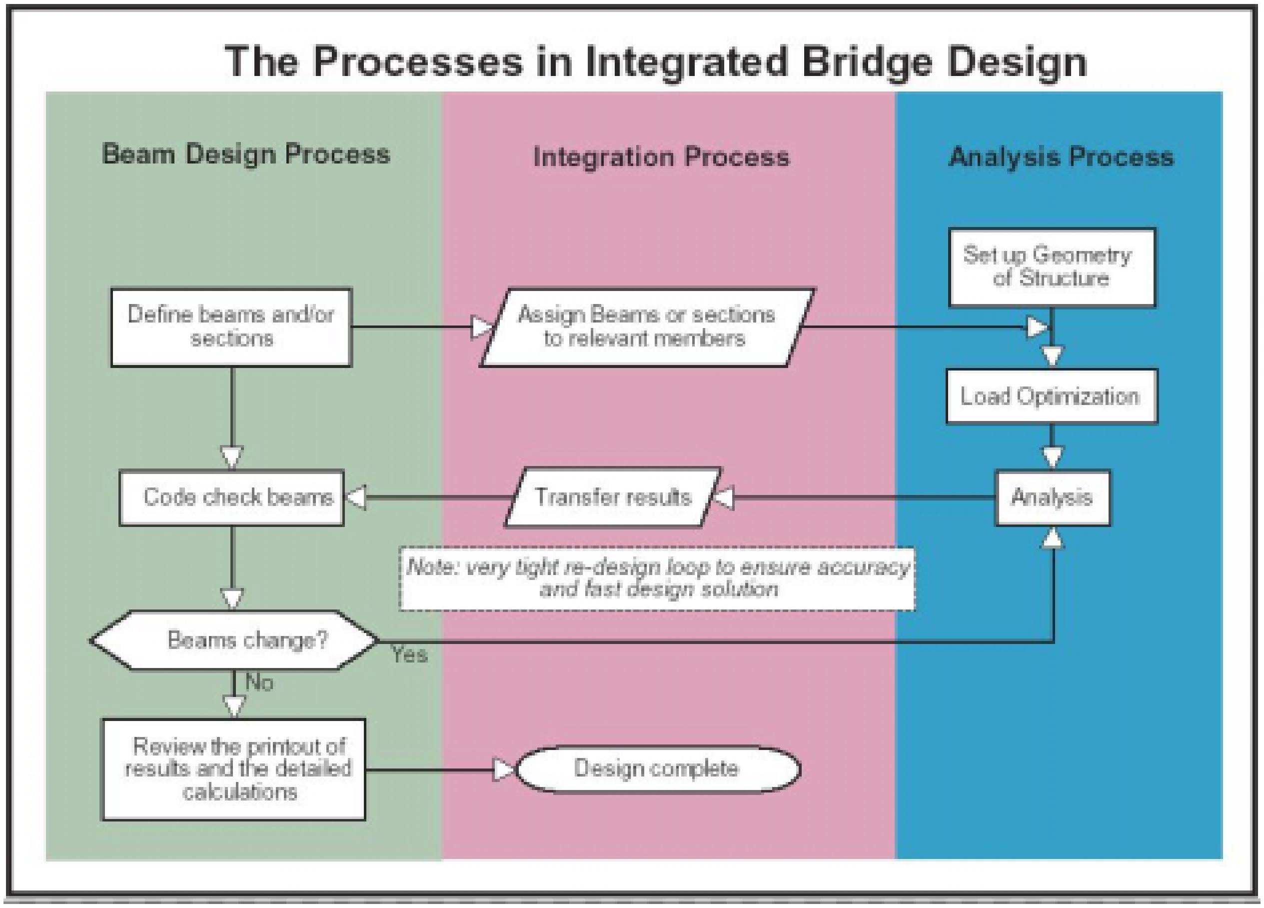

Figure 4.1 – Diagrammatic Illustration of the SAM Integrated Bridge Design Process

The benefits of integrated bridge design are as follows:

- A more focused approach to design, considering one detail or beam at a time;
- Section properties of complex beams are calculated automatically and re-calculated when sections change;
- Grillage or finite element parameters can easily be changed at any time in the process with very little extra work;
- Simple generation of influence surfaces for any beam, element, or “composite member”, combined with the influence loading technique, ensures fast and reliable production of all necessary load effects;
- Analysis results are transferred seamlessly to the integrated design modules;
- Fast and seamless iteration of the Analysis / Code-checking cycle.

5 CONCLUSION

The above three examples of recent software developments illustrate methods of simplifying bridge analysis and design. The advantages are summarized as follows:

- Automated Loading by the Influence Surface Method. This fully automates the production of the worst case set of load patterns to AS5100 and NZ Transit Manual and offers large savings in time and accuracy.

- Composite Analysis Method. This technique changes the way engineers can apply 3D frame and finite element models by resolving complex out of plane load effects to produce single bending moments and shears that can be used for design.

- Integrated Analysis and Design. This offers large design savings as the design/analysis cycle time is significantly reduced.

6 REFERENCES

1. MAXWELL, “Calculation of the Equilibrium and Stiffness of Frames”, *Phil. Mag* (April 1864)

2. MULLER BRESLAU, “Die Graphische Static der Baukonstruktionem”, *Bd. II, Adt. I, Suttgart, 5th ed.* (1922)