Bridge structures

9.2 Structural types of bridges

Based on their load path and structural behaviour, the main structural types of bridges are: beam bridges, truss bridges, cantilever bridges, arch bridges, suspension bridges, and cable-stayed bridges.

9.2.1 Beam bridges and truss bridges

A beam bridge is one of the simplest bridges due to its structural form. The bridge is simply supported at each end of the bridge decks. Thus no moments can be transferred throughout its supports, and in analysis the supports should be modelled as pinned. Common materials used in the beam bridge were stones or wood in ancient times, but in modern infrastructure reinforced concrete or steel are widely used. In steel beam bridges, the main beams can be formed either by trusses or box girders. The box section is widely used for short-span bridges, due to its good resistance to torsional moment.

Truss bridges belong to the beam bridge group but can also be categorised as an independent type of bridge. The truss structure is made from the connection of tension and compression structural members forming triangular units. Figure 9.1 shows an example of a truss beam bridge.

Fig. 9.1 Illustration of a truss beam bridge in London.

9.2.2 Arch bridges

The main structure members form a curved arch. These types of bridges utilise the arch action, which has the ability to transfer the gravity load – such as the dead and live – into a horizontal thrust that is controlled by the abutments of the bridge at each sideway. Therefore, one of the features of this type of bridge is that heavy abutments will be used.

Unlike the beam bridge, which is mainly in bending and shear, the key structure members are mainly in compression due to the arch shape. Traditionally, the materials used for the construction of an arch bridge are stone, brick or concrete, as these types of materials are very strong in compression but weak in tension and bending.

In modern construction, arch bridges made of steel members are also popular. One of the most famous examples is the Sydney Harbour Bridge, as shown in Figure 9.2.

9.2.3 Cantilever bridges

A cantilever bridge span is usually designed with two cantilever arms, which extend from opposite sides and join at the centre of the bridge. One famous project example is the Forth Bridge in Scotland (shown in Figure 9.3) which will be introduced in detail as a modelling example in Section 9.5.

9.2.4 Suspension bridges

The suspension bridge is a type of bridge used for long spans. It can achieve a longer main span than any other type of bridge. One famous example is the Golden Gate

Fig. 9.4 **Golden Gate Bridge in California.**
Photo from Structurae: International Database for Structural Engineering, courtesy of Wilhelm Ernst & Sohn Verlag.

Bridge (as shown in Figure 9.4). The main structural components of this type of bridge are: cables, supporting towers and vertical suspender cables that carry the weight of the bridge deck. Sufficient anchorages should be designed to hold the cables of the bridge.

The materials required for construction will be less than any other bridge of the same length and as a result the construction cost will be reduced. It can withstand earthquakes movements better than heavier bridges.

9.2.5 Cable-stayed bridges

Cable-stayed bridges are visually similar to suspension bridges. However, their structural behaviour is completely different. A typical cable-stayed bridge is a continuous girder with towers supported by the bridge's foundation. From these towers, cables extend down diagonally, usually to both sides, in order to support the girder. In the cable-stayed bridge, the towers form the primary load-bearing structure.

Compared to suspension bridges, the main advantage of this type of bridge is that there is no need for anchorages to hold cables. The cables work as a restraint to the bridge deck, providing greater rigidity, thereby reducing its deformation. In construction practice, these types of bridges are ideal for spans that are longer than those of the cantilever bridges but shorter than those of a suspension bridge. For span length up to 1000 m, cable-stayed bridges are considered the most economical.

One famous project example is the Millau Viaduct Bridge in France (shown in Figure 9.5) which will be introduced in detail in as a modelling example in Section 9.4.

Fig. 9.5 Millau Viaduct Bridge.
Photo from Structurae: International Database for Structural Engineering, courtesy of Wilhelm Ernst & Sohn Verlag.

9.3 Structural design of bridge structure

The design procedure of a bridge must take into consideration several important factors in order to reach a best solution. These are choices of bridge systems, materials, dimensions, foundations, aesthetics, local landscape and environment. Structural designers are required to provide the most effective structural solution with maximum safety and minimum cost.

In bridge design, superstructure mainly refers to the deck, beams, trusses and different accessories above the bridge, while substructure mainly refers to the mechanisms of the bridge that support the load from the superstructure and then transfer the load into the ground, such as columns, pier walls and piles.

9.4 Design loading

Design guidance such as Eurocode 1 (2003) or AASHTO (2007) gives detailed requirements of the design load when working on bridges. According to Eurocode 1 (2003), the following should be considered: self-weight and imposed loads, wind, thermal actions, actions during execution, accidental actions (impact loads) and traffic loads. There are also other actions such as concrete creep and shrinkage, settlements and earth pressures, or seismic actions that need to be considered.

Load models are developed for highway bridges in both Eurocode 1 (2003) and AASHTO (2007). The basic load combination for highway bridges is a simultaneous occurrence of dead load, live load and dynamic load. The models are based on the available statistical data on these loads.

In this section the major loads on the bridge superstructures and how these loads are distributed on the bridge will be illustrated. Readers can refer to the design specification mentioned in this chapter for further information.

9.4.1 Dead loads

According to the specifications of Eurocode 1 (2003), the dead loads that can exist in a bridge come from two parts. One is the structural part, such as the structural steel or the structural concrete, and these can be determined based on the dimensions of the structural elements. The other is the non-structural parts, such as concrete barriers, the surface and the deck cover on the bridge and any other elements considered as permanent loads by the engineer.

9.4.2 Live loads

The predominant live loading is traffic load on the bridge. The maximum live loads a bridge can support are based on the maximum number of vehicles that will pass over the bridge at a given time. Future growth of faster and larger moving transport should also be considered. In some cases it is important to use different measures and tests regarding the performance and behaviour of the structure under maximum load.

The effect of live load depends on many parameters including the span length, truck weight, axle loads, axle configuration, position of the vehicle on the bridge (transverse and longitudinal), number of vehicles on the bridge (multiple presence), girder spacing and stiffness of structural members (slab and girders). The effect of these parameters is considered separately (Nowak, 1993).

Eurocode 1 (2003) provides different traffic load models for the designer to use, they are as follows:

- Vertical forces: LM1, LM2, LM3, LM4.
- Horizontal forces: braking and acceleration, centrifugal, transverse.
- Groups of loads: gr1a, gr1b, gr2, gr3, gr4, gr5.

AASHTO (2007) also gives different traffic load model numbers. For example, trucks that have a load configuration larger than the allowed specifications and are named ‘Highway Load ’93’ or HL93.

9.4.3 Seismic effects on bridges

Earthquake load is another important consideration. Ground shaking or deformation is a primary cause of damage to the bridge, resulting in damage or collapse.

Superstructure designs have to be effectually durable to remain principally elastic during earthquakes.

9.4.4 Wind effects on bridges

The well-known collapse of Tacoma Narrows Bridge in 1940 (Billah and Scanlan., 1991) shows the importance of wind effect on long-span bridge performance. Extensive research has been carried out to investigate the effects of wind on long-span bridges such as suspension bridges or cable-stayed bridges and analysis of the response of the bridge under wind load. In certain situations, wind tunnel tests and detailed finite element dynamic models need to be developed.

9.4.5 Accidental actions (impact loads)

In bridge design it is also important to consider accidental actions such as the impact from ships. There are several scenarios of impact cases, such as bow collision with a bridge pillar or side collision or ship deckhouse collision with the bridge span and so on.

The factors that affect the impact load are: the type of waterway, the flood conditions, the type and draught of vessels and the type of structure (JCR-Ispra 2012).

9.5 Modelling example of Milau Viaduct using CSI Bridge

The Millau Viaduct was designed by Foster + Partners. It is a multi-span cable-stayed structure that has been claimed to be currently the tallest bridge in the world. It consists of eight spans; six central spans of 342 m each and two end spans of 204 m. In total, it has a complete length of 2460 m. The pylons are set into the deck in both the longitudinal and transverse direction. This is to ensure continuity between the metal sheets of the central box girder and those of the walls of the pylon legs and also to provide rigidity through a frame that covers the bearings found on each pier shaft. The deck is in the form of a trapezoidal profiled steel girder box with a depth of 4.20 m with an orthotropic decking made up of metal sheets.

Two models are set up based on the architectural drawings provided by Foster + Partners (as shown in Figure 9.6). One is a 3D SAP2000 model of Millau Viaduct (as is demonstrated in Figure 9.7). Similar modelling techniques will be introduced in Section 9.6 to model the Forth Bridge in Scotland. Here, in order to demonstrate how to model a bridge in CSI Bridge, the model will be set up in CSI Bridge and for demonstration purposes only two spans are modelled. The detailed steps will be introduced here.

9.5.1 Model set up

- Launch CSI Bridge as shown in Figure 9.8, click on *New Model*. The model will be constructed from a blank model and the units are set to KN, m.

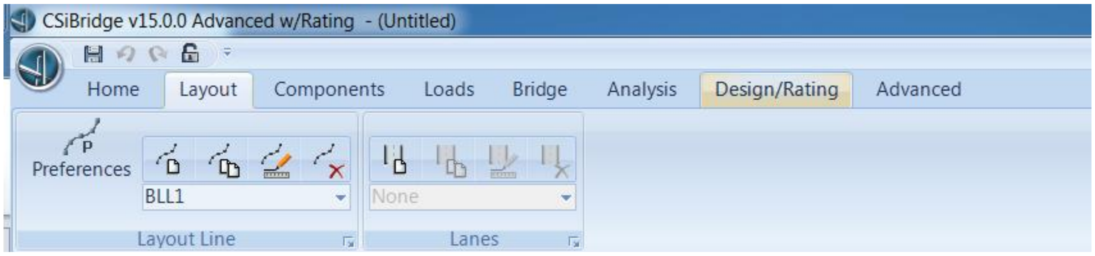

Fig. 9.9 Layout module.
SAP2000 screenshot reprinted with permission of CSI.

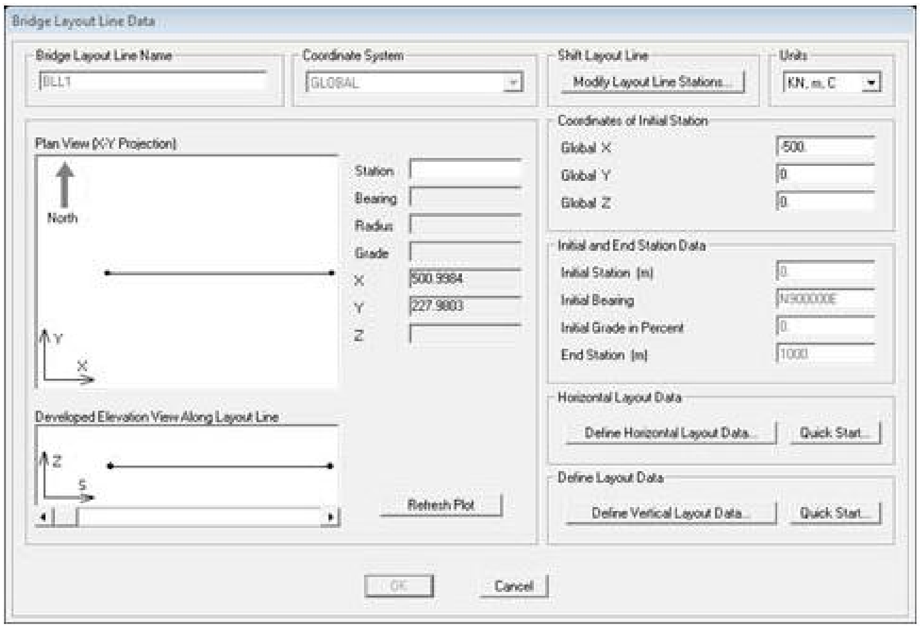

Fig. 9.10 Defining the bridge layout.
SAP2000 screenshot reprinted with permission of CSI.

Define the layout

- Go to *Layout Line* – click on *Add New Layout Line* as shown in Figure 9.9.
- A new window will pop up (Figure 9.10). The layout of the bridge will be defined; this is to set the origin of the bridge in order to establish a coordinate system. Defining the origin is mandatory, as when inserting bridge components at a later stage users must insert objects using coordinates and they are also used to set dimensions.
- Selecting the *Components* tab (Figure 9.11), then go to the *Type Menu* and set frame properties for the towers. Similar to SAP2000, the material and section type can be created within this operation. For this example, a uniform section has been selected; however, if a non-uniform section needed to be employed, this would need to be done via the non-prismatic section menu. The objects would need to be created separately and then combined using the non-prismatic menu.

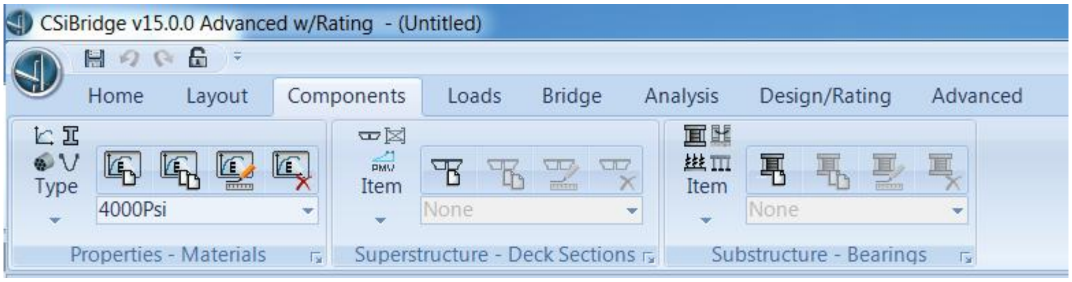

Fig. 9.11 **Bridge component module.**
SAP2000 screenshot reprinted with permission of CSI.

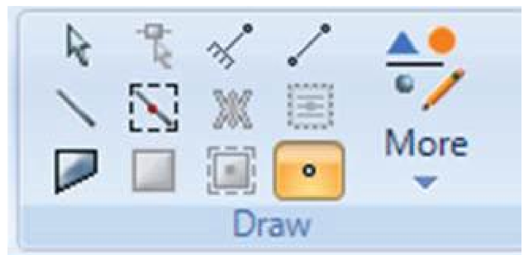

Fig. 9.12 **Selecting frame elements from draw module.**
SAP2000 screenshot reprinted with permission of CSI.

Define the tower

- Switch to 'XY' view at Y = 0. Extra features will have to be used when drawing the towers as they are not standard components.
- Selecting the draw *Frame* (Figure 9.12) command and setting the properties object box to *Pylon* (pre-defined name), the user can draw the Tower and edit the height and location of each respective point using the 'joint coordinates' editor.
- Joints are created along the tower to provide for the cable connections. One joint is created at a specified location by the user. Other joints can then be simply added by using the replicate command.

Define the deck sections

- Select the *Components* tab. A new deck is selected from the menu (Figure 9.13); various types are available in different materials. For the cable-stayed bridge, steel girders were selected. The software allows the user to input the dimensions of the deck.

Cable connections

- The cable connections located at the deck must be defined; go to the *Bridge* module, click on the *Span Items* tab as shown Figure 9.14.
- The user points command is then used to divide the deck into the required segments as shown Figure 9.15.

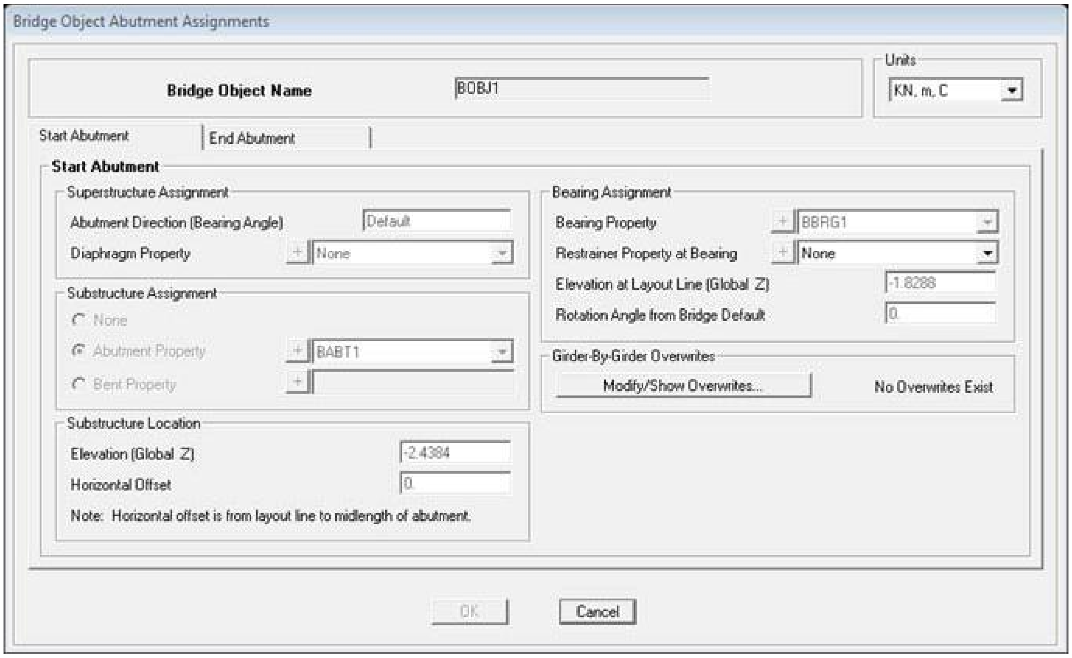

Fig. 9.16 Abutment definition menu.
SAP2000 screenshot reprinted with permission of CSI.

9.6 Defining abutments

- CSI Bridge provides a catalogue of different abutment types. Go to the *Bridge* tab and click on the *Supports* menu. Bearing can be modified within the abutments to allow for movements in the direction required, as shown in Figure 9.16.

Define the rigid links

- As the locations of the cables have been defined along the deck and tower, rigid links will now be placed in these positions. These will form the connection between the deck and cable. Users can define restrictions on movements depending on which movements are preferred.
- This option can be found in the *Advanced* tab and *Rigid Link* menu.

Defining the cables

- CSI Bridge allows users to define cables either by inputting a cross-sectional area or a diameter. Material properties can also be altered to replicate the steel that will be employed on site.
- This option can be found under the *Components* tab by selecting *Cable Properties*. When drawing the cables, the user must start from the joint of the tower and join to the required rigid link. It is important to take care as the cable could be connected to the wrong link.

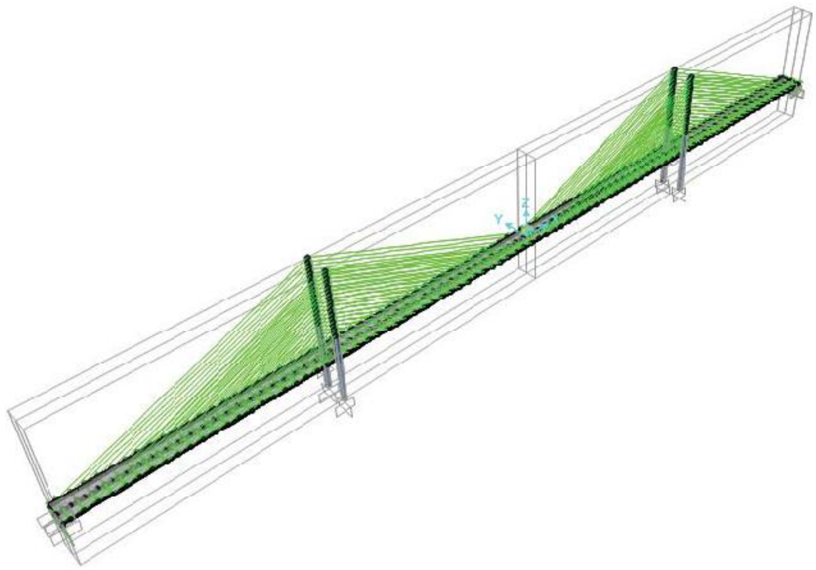

Fig. 9.17 3D bridge model in CSI Bridge.
SAP2000 screenshot reprinted with permission of CSI.

Fig. 9.18 Loads module.
SAP2000 screenshot reprinted with permission of CSI.

Final model

Following the above steps, the model has been set up as shown Figure 9.17.

9.6.1 Define the vehicle loading

In bridge design, vehicle loading is one of the most important considerations; in this section, we are going to introduce how to define vehicle loading in CSI Bridge.

1. Click on the *Loads* module (Figure 9.18).
   - Go to *Types*; under the *Vehicle* tab click on *Vehicles – Add A New Vehicle*; a new window will pop up as shown in Figure 9.19.
   - Choose vehicle type *HSn-44*, which is a truck.
   - Go to *Types* again; click on *Vehicles Classes – Add A New Vehicle Class*; a new window will pop up as shown in Figure 9.20.
   - Add a new vehicle class with the name *VECL1*, choose the vehicle we just defined, click *Add* (Figure 9.20).

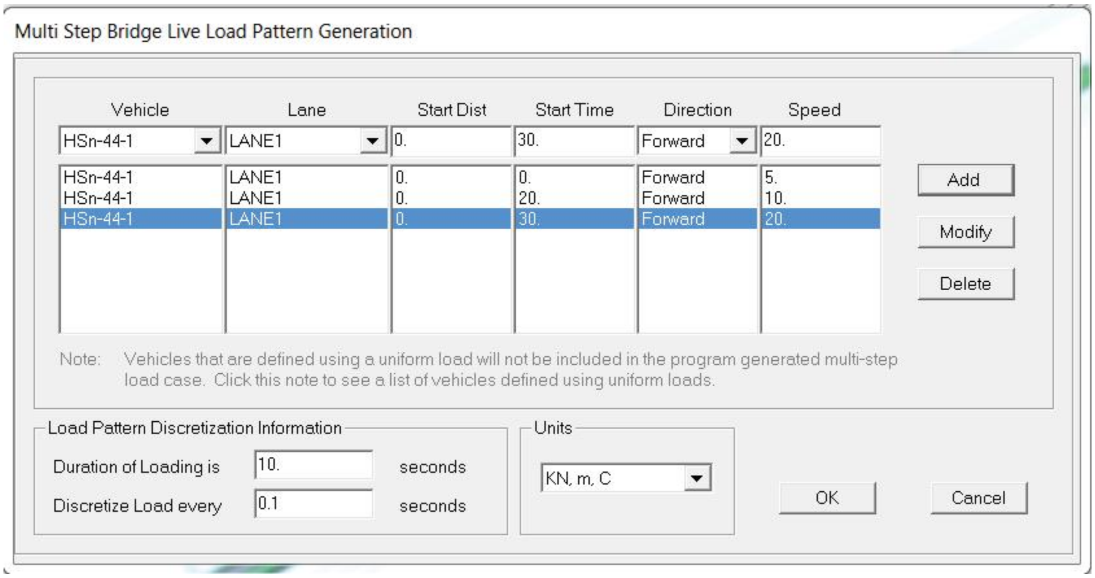

Fig. 9.21 Defining the bridge live load pattern.
SAP2000 screenshot reprinted with permission of CSI.

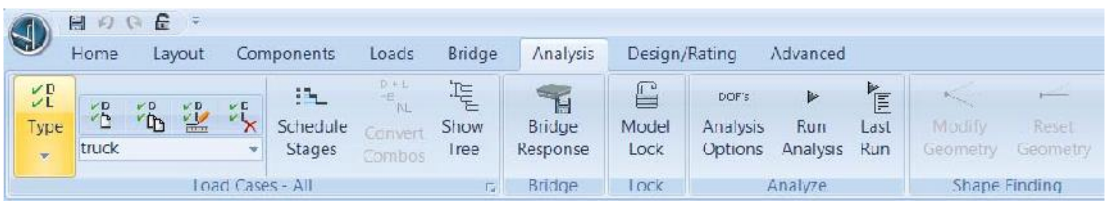

Fig. 9.22 Analysis module.
SAP2000 screenshot reprinted with permission of CSI.

- Click on *Load Patterns*; add a new *Load Pattern Class* with the name *Traffic*, type *Bridge Live*, add three vehicle durations with different starting times and different speeds as shown in Figure 9.21.

2. Click on *Analysis Module* (Figure 9.22).
   - Go to *Load Cases* tab – click on *Add A New Load Case*; a new window will pop up as shown in Figure 9.23.
   - A new window will pop up as shown in Figure 9.24.
   - Give the name *Traffic*.
   - Change the *Load Case Type* into *Time History*.
   - Add *Load Pattern*, choose the pattern we just defined.
   - Set up the remaining parameters as shown in Figure 9.24.
3. Run *Analysis*.

9.6.2 Analysis and result

After analysis, the results such as bending moment, shear force and deflection can be checked. Figure 9.25 gives an example of the analysis results.

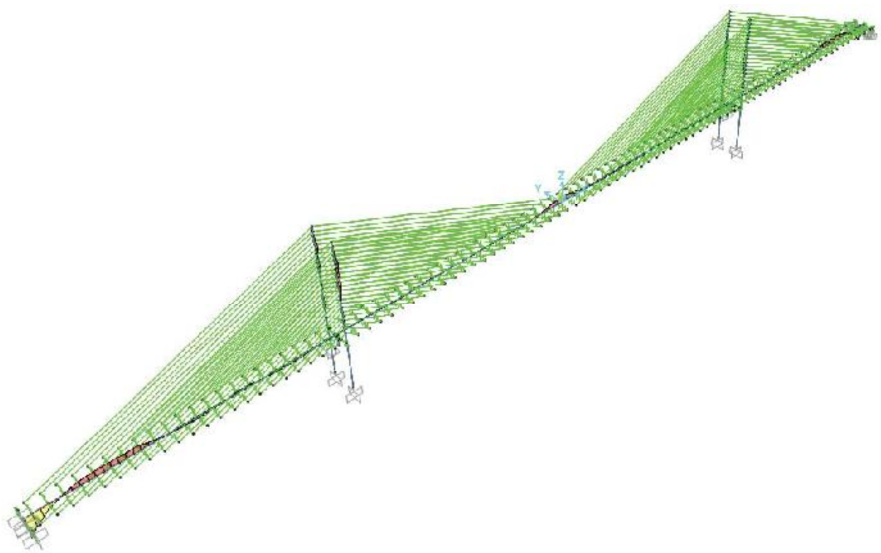

Fig. 9.25 **Bending moment diagram.**
SAP2000 screenshot reprinted with permission of CSI.

9.7 Modelling example of Forth Bridge using SAP2000

For more complicated bridge geometry, SAP2000 is another good program for modelling. For lower versions of SAP2000, if a license for the Bridge module is purchased, you can perform the same analysis as in CSI Bridge. Here, we are going to use the Forth Bridge in Scotland as a prototype to demonstrate how to model it in SAP2000.

The Forth Rail Bridge was built in 1890. The primary objective of this bridge is to connect the two coasts of Scotland. The structural engineering and other construction methodologies used in this bridge are still amazing in current world engineering and technology.

Sir Benjamin Baker came up with a design for a suspended cantilever bridge made up of six cantilever spans held in place by three towers and two spans in the middle to connect the cantilever spans to the towers. To connect this whole structure to either side of the coast, two approach viaducts were constructed with a number of abutments to fix the ends of the cantilever at both ends. The foundations were sunk at identical intervals across the whole width to achieve symmetry for the whole structure. The bridge behaves similarly to a typical truss, where the members are in compression and tension.

In this model, the member size and properties were taken from the introduction on the web and member dimensions were scaled according to photos on the web.

Step 1: Set up a 3D model in AutoCAD

The first step is to set up AutoCAD 3D-wireframe model and import it to SAP2000 as a .DXF file.

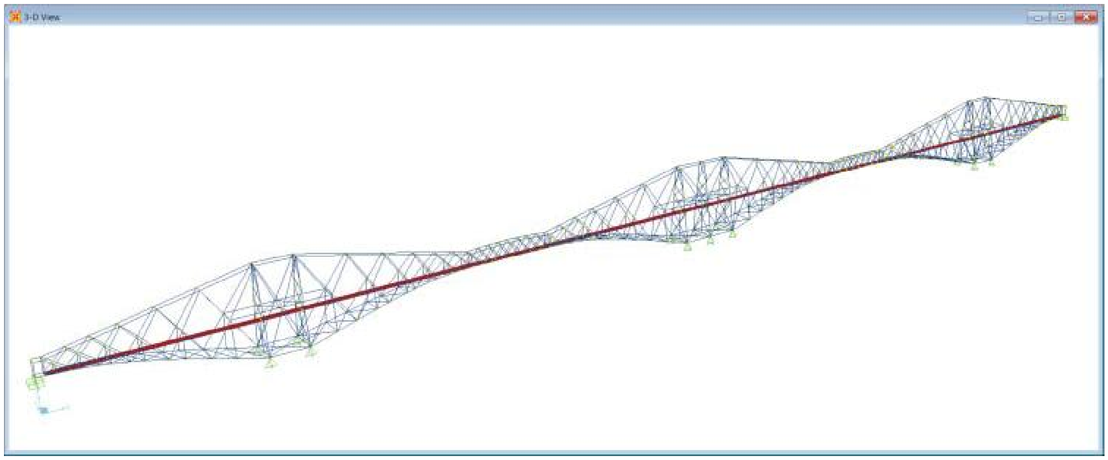

Fig. 9.26 **3D Forth Bridge model in SAP2000.**
SAP2000 screenshot reprinted with permission of CSI.

Step 2: Import 3D models in AutoCAD into SAP2000

Similar to that mentioned in other chapters, after importing the structural frame sequentially from different layers of AutoCAD, it is convenient to place the members from each layer into the same group. This will facilitate the future modification of the member.

Figure 9.26 shows the model after importing into SAP2000.

Step 3: Defining member properties and member size

- Go to *Define – Section Properties – Frame Sections*.

Each member material property was assumed to be Fy50 steel from reference, and this is defined with the properties shown in Figure 9.27.

The bridge was modelled using both box and tubular sections. The design check was run through using the design module in SAP2000.

Step 4: Defining the deck

The deck of the bridge consists of an internal viaduct with three rail tracks. The deck is modelled with a thin shell member (as shown in Figure 9.28) with a thickness of 250 mm, which is an approximated dimension. Viaduct or individual track members are ignored; however, their weights have been added as dead load in the analysis.

Step 5: Defining moving load cases

In the bridge design, the moving load of the vehicle is an important consideration. Here we are going to demonstrate how to model it in SAP2000. The other load cases, such as dead and other types of live load, will be defined in the same way as introduced in other modelling examples.

- Go to *Define* – click on *Bridge Loads, Lanes* as shown in Figure 9.29.
- A new window will pop up as shown in Figure 9.30.

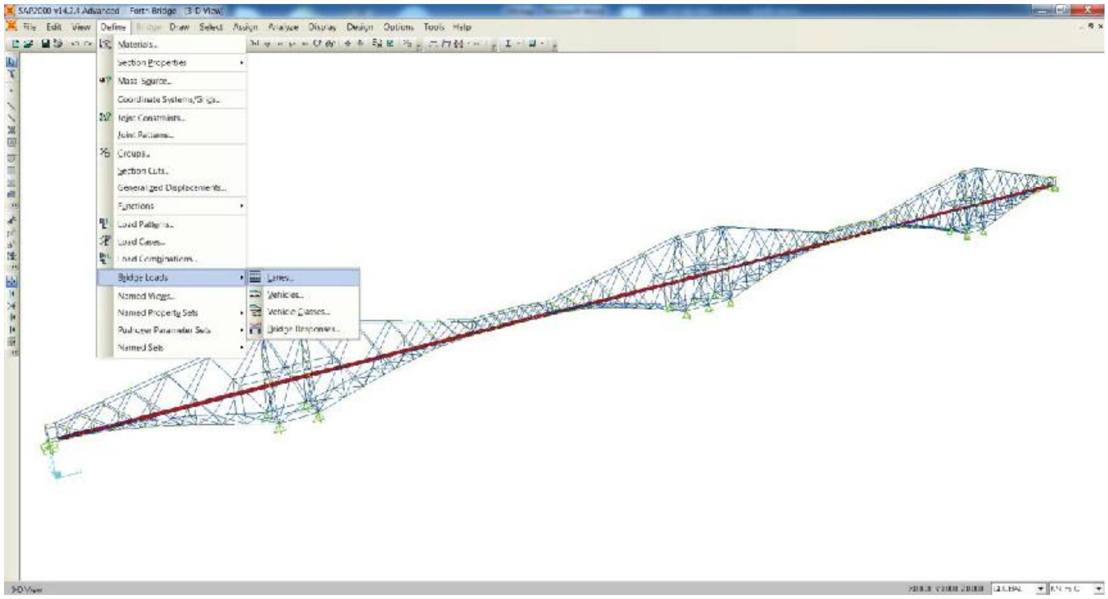

Fig. 9.29 Selecting the bridge loads module.
SAP2000 screenshot reprinted with permission of CSI.

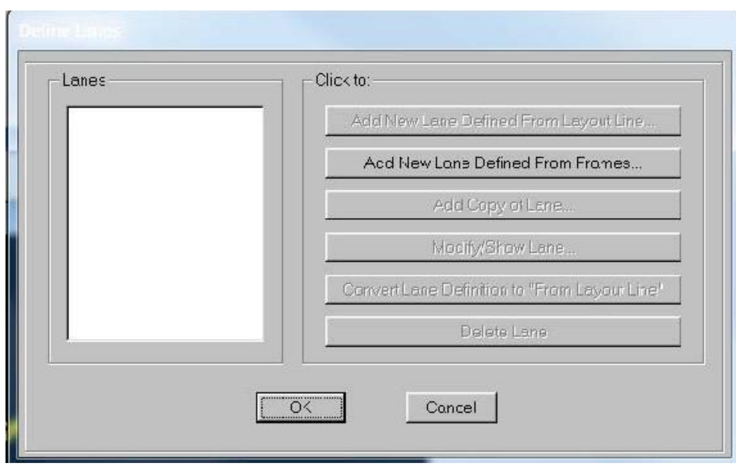

Fig. 9.30 Define the lanes.
SAP2000 screenshot reprinted with permission of CSI.

- Click on *Add New Lane Defined From Frames*.
- A new window will pop up (Figure 9.31).
- Go to *Set Display Options*, switch on the *Frame/Cable/Tendons – Labels*, the frame number will be shown in Figure 9.32.
- Put in the ID number of the frame element where you want to define the lanes. Here, the display colour is green, so after the definition the frame elements chosen will be highlighted green (as shown in Figure 9.32).
- Go to *Define* –click on *Bridge Loads – Vehicles*.
- A new window will pop up (Figure 9.33).
- Click on *Add General Vehicle*.
- A new window will pop up; add the new vehicle load as shown in Figure 9.34.

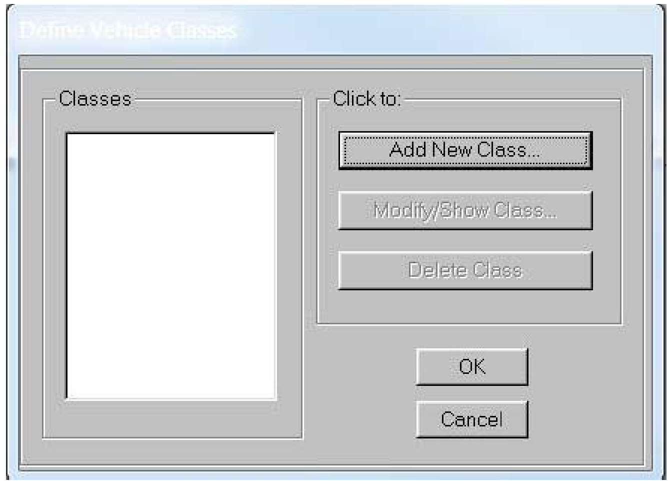

Fig. 9.35 **Adding the vehicle class.**
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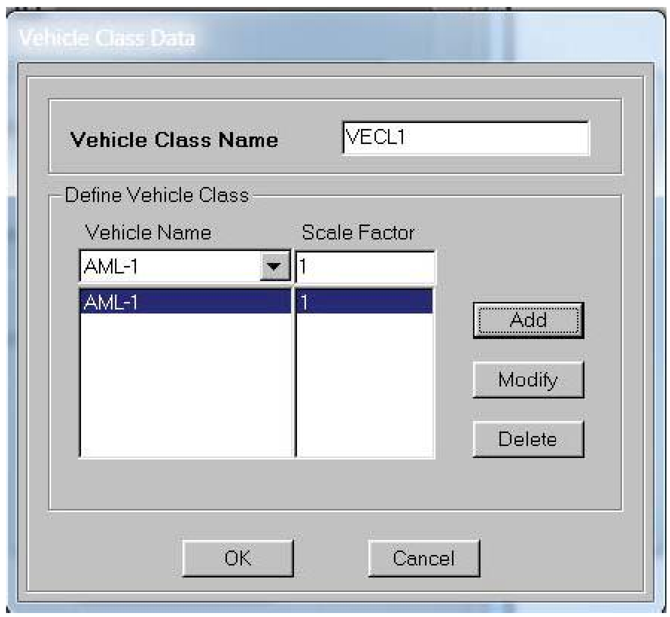

Fig. 9.36 **Selecting the vehicle class.**
SAP2000 screenshot reprinted with permission of CSI.

- Go to *Define* – click on *Bridge Loads – Vehicles Classes*; a new window will pop up (Figure 9.35).
- Click on *Add New Class*, a new window will pop up as shown in Figure 9.36, add the new vehicle classed as shown below.
- Go to *Define – Load Cases – Add New Load Cases*, a new window will pop up as shown Figure 9.37; add the moving load as below.

Make sure you provide the time history data for the *Moving Load* analysis.

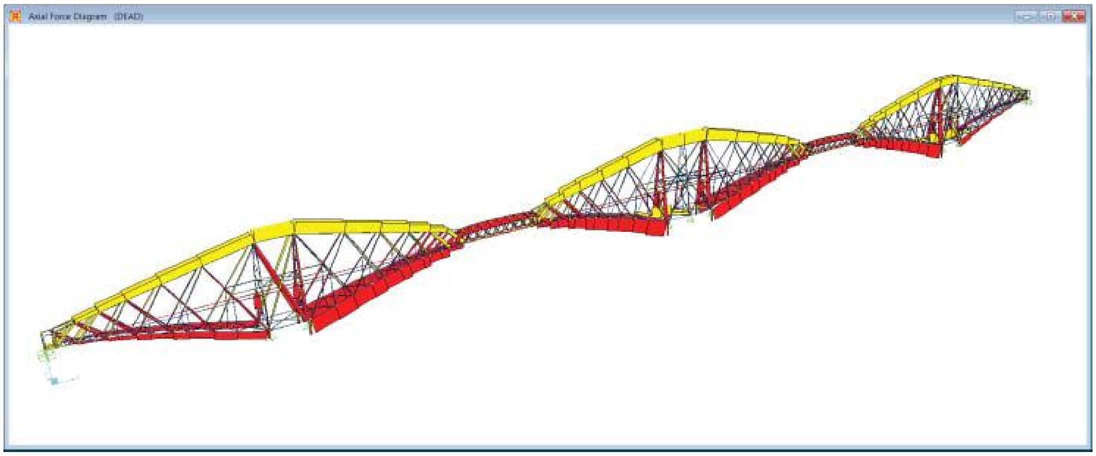

Fig. 9.39 Result of axial force due to dead load.
SAP2000 screenshot reprinted with permission of CSI.

Step 6: Analysis and result

After the setting up, the model is analysed and the result can be interpreted. Figure 9.38 shows the bending moment under the moving load case at the centre of the bridge.

Figure 9.39 shows the axial force under the dead load case of the bridge.