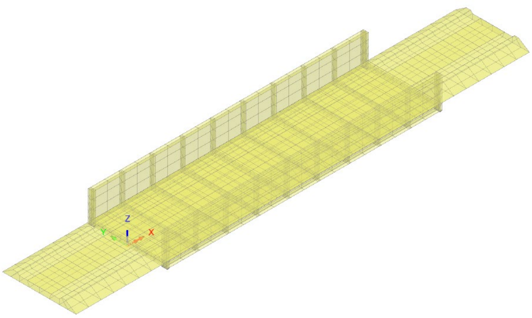
Train Induced Vibration of a Bridge

For LUSAS version:	21.1
For software product(s):	Any Plus version
With product option(s):	IMDPlus
Note: The example exceeds the limits of the LUSAS Teaching and Training Version.	

Description

This example examines the response of a steel rail bridge to the passage of a train.

Units used are N, m, kg, s, C throughout.



Objectives

The output requirements of the analysis are:

- Deflections in the X-, Y- and Z-directions for a train speed of 15 m/s
- Accelerations in the vertical direction for a train speed of 70 m/s
- Peak deflections and accelerations in the vertical direction for a speed range of 15 m/s to 70 m/s in 5 m/s intervals
- Stress resultants and peak stress resultants in main girder web.

- ❑ Averaged and peak vertical displacements and resultant dynamic amplification factors from all of the nodes of the bridge structure
- ❑ Total summed reactions and peak reactions from all of the supported nodes of the bridge structure
- ❑ Averaged and peak stresses for a side panel of the bridge structure

Keywords

3D, Moving Load, Time Domain, Response, Interactive, Modal, Dynamics, IMD, IMDPlus, Eigenvalue.

Associated Files

Associated files can be downloaded from the user area of the LUSAS website.

- ❑ **IMDPlus_rail_bridge.lvb** Creates a model of the structure.
- ❑ **ec1-3 Type3.lmd** This is an atribute library that contains the Eurocode ENV 1991-3 Type 3 moving load train definition for the example.
- ❑ **ec1-3 Type3.xls** A Microsoft Excel spreadsheet that contains the axle positions and loads of the Eurocode ENV 1991-3 Type 3 train set.

Modelling

Running LUSAS Modeller

For details of how to run LUSAS Modeller, see the heading ***Running LUSAS Modeller*** in the Examples Manual Introduction.

Creating a Model

File
New…

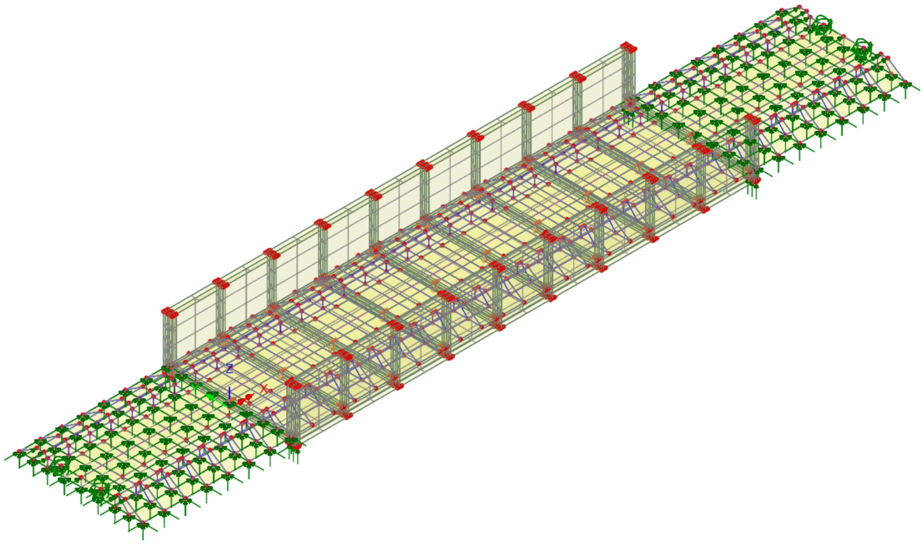
- Enter a file name of **IMDPlus_rail_bridge.mdl**
- Use the default **User-defined** working folder.
- Ensure an Analysis type of **3D** is set.
- Click the **OK** button.

Note. There is no need to enter any other new model details when the intention is to run a script to build an initial model, since the contents of the script will overwrite any other settings made.

File
Script >
Run Script…

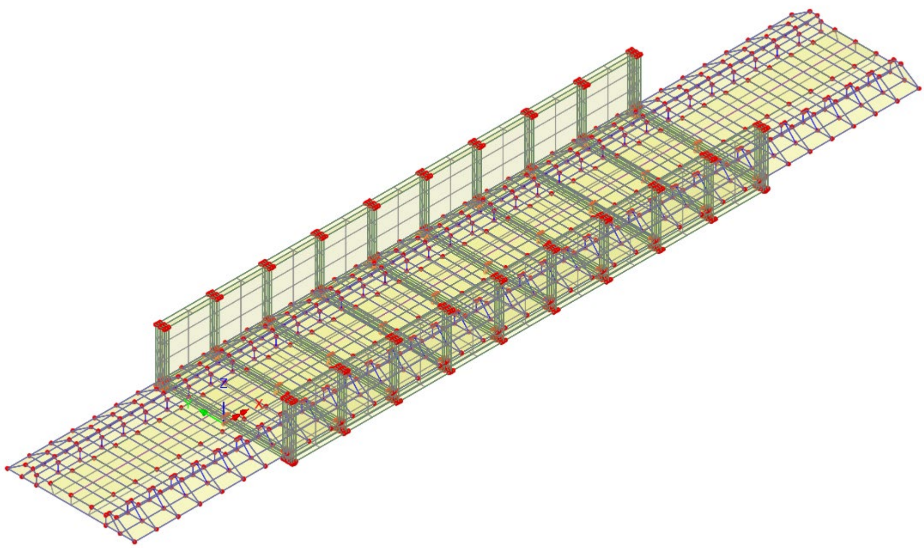
- To create the model, open the read-only file **IMDPlus_rail_bridge.lvb** that was downloaded and placed in a folder of your choosing.

Once opened, after a short while the following view of the model of the bridge will be displayed.



File
Save As…

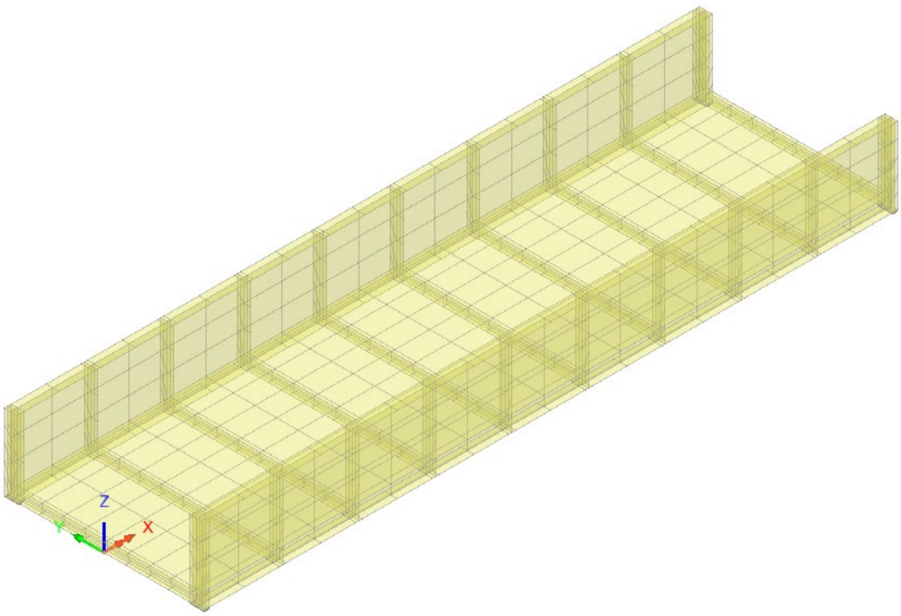
- Create a new project folder called **IMDPlus_rail_bridge** and save the model into this new folder. This helps keep all relevant IMDPlus created files separate from other analyses and is good practice.
- Turn off the display of the **Attributes** layer in the Treeview.



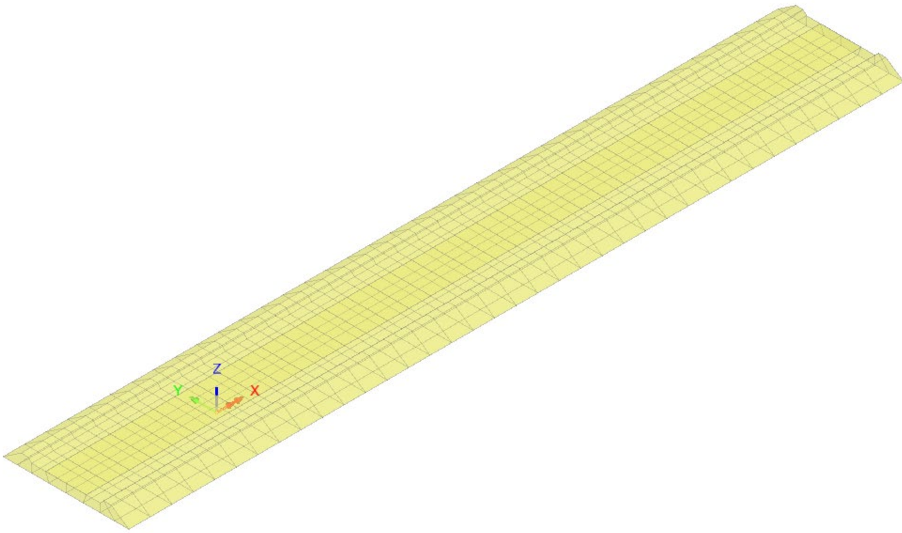
Note. No static structural loading is required for this analysis because only the dynamic loading is considered during the results processing, which is defined later.

Modelling Discussion

The bridge is approximately 16.5m long and 4.75m wide and carries a single track with ballast and concrete sleepers. The primary structure is constructed from steel and is modelled using shell elements. For this analysis, modelling of the ballast/track-bridge interaction has been carried out using a full 3D solid representation of the ballast with the sleepers modelled with thick beam elements laid along the top of the ballast. The rails of the track have been modelled using thick beam elements spanning between the sleepers and the whole ballast/track model is connected to the bridge deck using a sliding-only slideline. For the purposes of this example the bridge and ballast model has been represented with a coarse mesh and therefore the results from this analysis will be less accurate than the use of a finer mesh. For analysing actual structures it is recommended that a finer mesh be used which can capture both the vibration modes of the bridge and the movement of the load across the bridge more accurately.

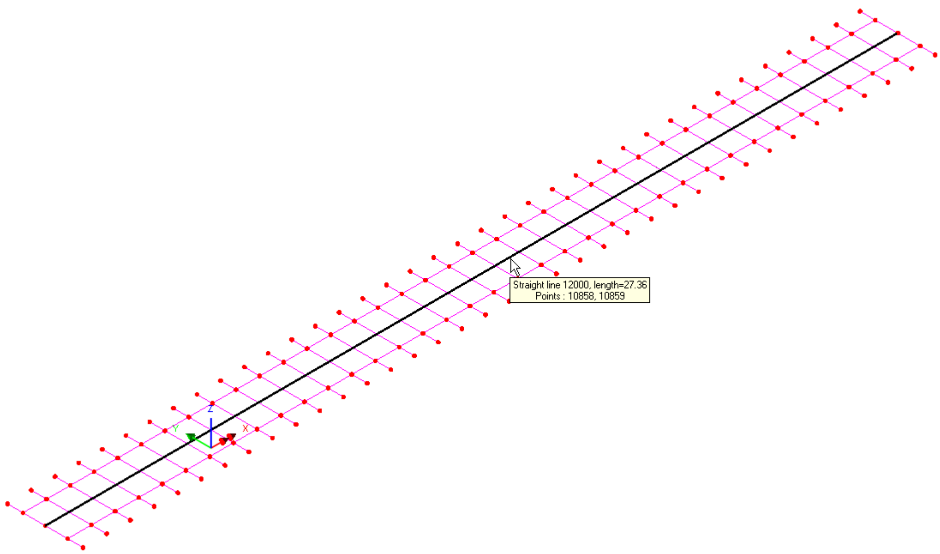


Bridge representation



Ballast representation

To allow the loading of the rails to be distributed to the 3D solid elements using discrete point loads the track modelling uses weak, weightless shell elements which span between the beam elements representing the rails. The track representation is shown in the following figure.



Track (sleepers and rails) representation

Note that the line down the centre of the track (Line 12000) is used to define the path of the train across the bridge and will be used later in this example. In order to avoid any adverse dynamic behaviour of the weak weightless shell elements, only one division is used to span between the two rails thus providing full support to the shells without adding stiffness to the model.

Defining Eigenvalue Controls

Eigenvalue controls are defined as properties of the loadcase.

- In the Treeview expand **Analysis 1** then right-click on **Loadcase 1** and select **Eigenvalue** from the **Controls** menu.

The Eigenvalue dialog will appear.

The following parameters need to be specified:

- Set the Eigenvalues required to **Range**
- Ensure the Range is set to **Frequency**
- Set the Minimum frequency as **0**
- Set the Maximum frequency as **35**
- Set the Number of eigenvalues to **0** (this solves for ALL frequencies in the range)
- Ensure the Type of eigensolver is set as **Default**

Note. Eigenvalue normalisation is set to **Mass** by default. This is essential if the eigenvectors are to be used for subsequent IMD analysis.

- Click the **OK** button to finish.

File
Save

Save the model file.

Running the Analysis

- With the model loaded click the **Solve** button and the **Solve Now** dialog will be displayed.
- Click the **OK** button to run the analysis.

A LUSAS Datafile will be created from the model information. The LUSAS Solver uses this datafile to perform the analysis.

Viewing the Results

If the analysis was run from within LUSAS Modeller the results will be loaded on top of the current model and the loadcase results for each eigenvalue can be seen in the Loadcase layer. Eigenvalue 1 is set to be active by default.

Checking the Mass Participation Factor

Note. In order to carry out a successful IMDPlus analysis you should ensure that a significant proportion of the total mass has been accounted for in the analysis. This requires checking that around 90% of the total mass has been achieved in the global directions. If less than 90% has been achieved no further modes need be included, if and only if, the modes of vibration omitted cannot be excited by the dynamic input or a significant proportion of the structure is restrained by support in these directions and therefore cannot participate in the modes of vibration. The acceptability of the included modes of vibration will vary from analysis to analysis but failure to check that a significant proportion of the total mass has been accounted for may lead to important modes being missed and subsequent errors in the analysis results.

Utilities
Print Results Wizard…

- Select results type **Eigenvalues**. For loadcase 1, in the available results panel select **Sum mass participation factors** and click **OK.** The results will be displayed, and a Print Results Wizard entry will be added to the Utilities treeview.

LUSAS View: IMDPlus _rail_bridge.mdl Window 1 | Sum mass participation factors

	Mode	Sum Mass X	Sum Mass Y	Sum Mass Z	Frequency	Period
1	1	0.0111762	16.5213E-6	0.70681	6.35097	0.157456
2	2	0.012301	17.5145E-6	0.706921	9.78044	0.102245
3	3	0.0126563	0.201211	0.707195	11.9579	0.0836264
4	4	0.0133135	0.201221	0.76798	12.576	0.0795166
5	5	0.0351538	0.825051	0.769658	16.2725	0.0614534
6	6	0.0358118	0.849593	0.769926	16.4299	0.0608646
7	7	0.183829	0.898386	0.80477	17.0919	0.0585073
8	8	0.184235	0.90008	0.830182	19.4189	0.0514961
9	9	0.218193	0.901224	0.831635	23.9345	0.0417807
10	10	0.250231	0.901341	0.833605	24.0917	0.0415081
11	11	0.880527	0.90147	0.861113	24.5365	0.0407556
12	12	0.903429	0.943281	0.8619	25.3362	0.0394692
13	13	0.924662	0.943478	0.862841	28.139	0.0355379
14	14	0.924694	0.944287	0.862844	28.284	0.0353557
15	15	0.924762	0.944475	0.880501	28.9023	0.0345994
16	16	0.940955	0.944483	0.881134	32.3357	0.0309256
17	17	0.940957	0.944753	0.881134	33.6284	0.0297367
18	18	0.940989	0.944761	0.881135	34.584	0.0289151
19	19	0.941005	0.944847	0.881135	34.9625	0.0286021

By inspection it can be seen that the 90% value has almost been achieved in all directions for this analysis. This is discussed in the note below.

Note. In this analysis we are only including modes of vibration with frequencies up to and including 35 Hz with frequencies higher than this value considered insignificant for the analysis. In this analysis (and for mode 19) the results show that 94% of the total mass is achieved in the X-direction, 94% is achieved in the Y-direction and 88% is achieved in the Z-direction.

- Close the results window.

Utilities
Print Results Wizard…

- Select results type **Eigenvalues**. For loadcase 1, in the available results panel de-select **Sum mass participation factors**, then select **Mass participation factors** and click **OK.**

The results will be displayed, and a Print Results Wizard entry will be added to the Utilities treeview

LUSAS View: IMDPlus _rail_bridge.mdl Window 1 | **Mass participation factors**

	Mode	Mass PF X	Mass PF Y	Mass PF Z	Frequency	Period
1	1	0.0111762	16.5213E-6	0.70681	6.35097	0.157456
2	2	1.12477E-3	0.993205E-6	0.11053E-3	9.78044	0.102245
3	3	0.355329E-3	0.201194	0.274654E-3	11.9579	0.0836264
4	4	0.657132E-3	9.54664E-6	0.0607852	12.576	0.0795166
5	5	0.0218404	0.62383	1.67767E-3	16.2725	0.0614534
6	6	0.657934E-3	0.0245415	0.267876E-3	16.4299	0.0608646
7	7	0.148018	0.0487933	0.0348435	17.0919	0.0585073
8	8	0.40572E-3	1.69459E-3	0.0254123	19.4189	0.0514961
9	9	0.0339575	1.14388E-3	1.45348E-3	23.9345	0.0417807
10	10	0.0320381	0.116338E-3	1.96941E-3	24.0917	0.0415081
11	11	0.630296	0.129627E-3	0.0275085	24.5365	0.0407556
12	12	0.0229019	0.0418103	0.786394E-3	25.3362	0.0394692
13	13	0.0212328	0.197928E-3	0.941292E-3	28.139	0.0355379
14	14	32.042E-6	0.808706E-3	2.90818E-6	28.284	0.0353557
15	15	68.0917E-6	0.187872E-3	0.0176574	28.9023	0.0345994
16	16	0.0161925	7.93875E-6	0.633004E-3	32.3357	0.0309256
17	17	2.5144E-6	0.270408E-3	0.322803E-6	33.6284	0.0297367
18	18	31.9051E-6	7.18089E-6	0.193415E-6	34.584	0.0289151
19	19	15.885E-6	86.5752E-6	13.7149E-9	34.9625	0.0286021

From these mass participation factors the major modes of vibration of the bridge can be seen to be mode 1 in the Z-direction (vertical), mode 5 in the Y-direction (lateral) and mode 11 in the X-direction (longitudinal).

- Close the results window.

Plotting Mode Shapes

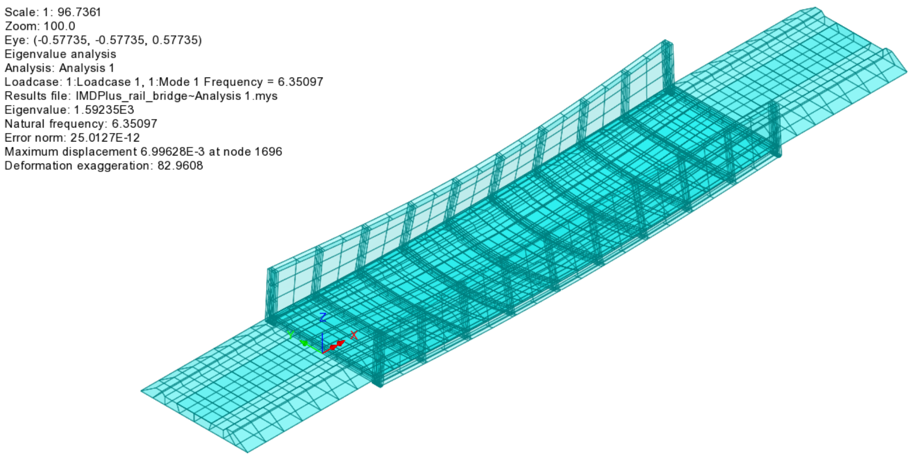
- Turn off the display of the **Mesh,** and **Geometry** layers in the Treeview.

- With no features selected click the right-hand mouse button in a blank part of the View area and select the **Deformed mesh** option to add the deformed mesh layer to the Treeview. Click the **OK** button to accept the default values and display the deformed mesh for Eigenvalue 1.

- If supports are shown click on the Supports on/off button to remove the supports from the display.

- In the panel at the bottom of the Treeview select the **Window summary** option and click the **Details...** button. In the Window summary properties dialog set the position to **(15.0,-15.0)** and click the **OK** button to return to the view window.

This mode of vibration is the primary mode in the vertical direction as determined in the section titled ‘Checking the Mass Participation Factor’.

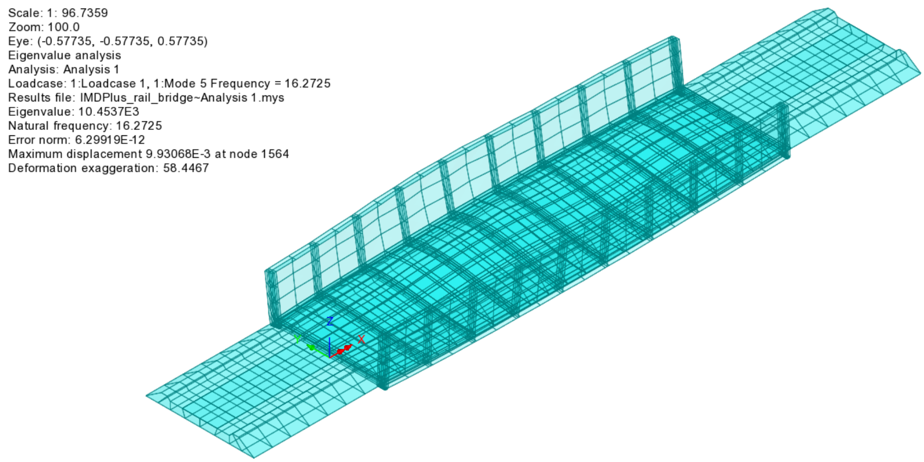


By setting each Eigenvalue to be active the deformed mesh can be seen for all mode shapes.

Note. The mode shapes may be inverted. This is because the sense is arbitrary since during vibration the deformed shape will appear in both directions.

- In the Treeview right-click on **Mode 5 Frequency = 16.2725** and select the **Set Active** option. The deformed mesh plot for this eigenmode will be displayed.

This mode of vibration has the highest participating mass in the lateral (Y) direction for the whole bridge as determined in the ‘Checking the Mass Participation Factor’ section.



Note. The window summary displays the values of the eigenvalue and the natural frequency and also a value for displacement at a node. It should be noted that the displacement value is non-quantitative and is related to the amount of mass in a particular mode using the mass normalisation technique. Therefore the only items that can be found using a basic eigenvalue analysis are the frequency and the mode shape.

Selecting individual nodes and elements of interest

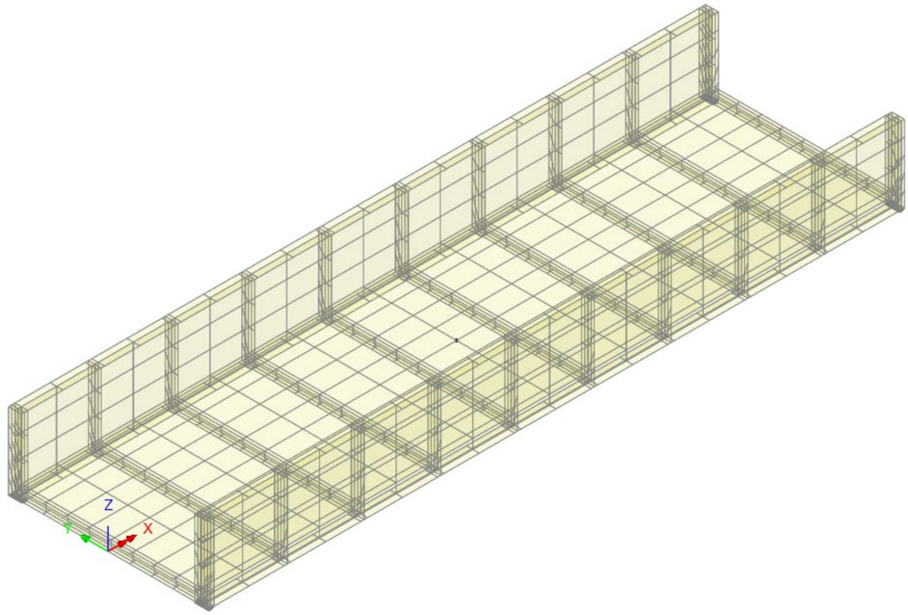
Prior to running an IMDPlus analysis, individual node and element numbers for the locations of the structure that will be assessed should be ascertained. This can be done by selecting the locations of interest with the cursor and noting down the numbers of the node and elements concerned.

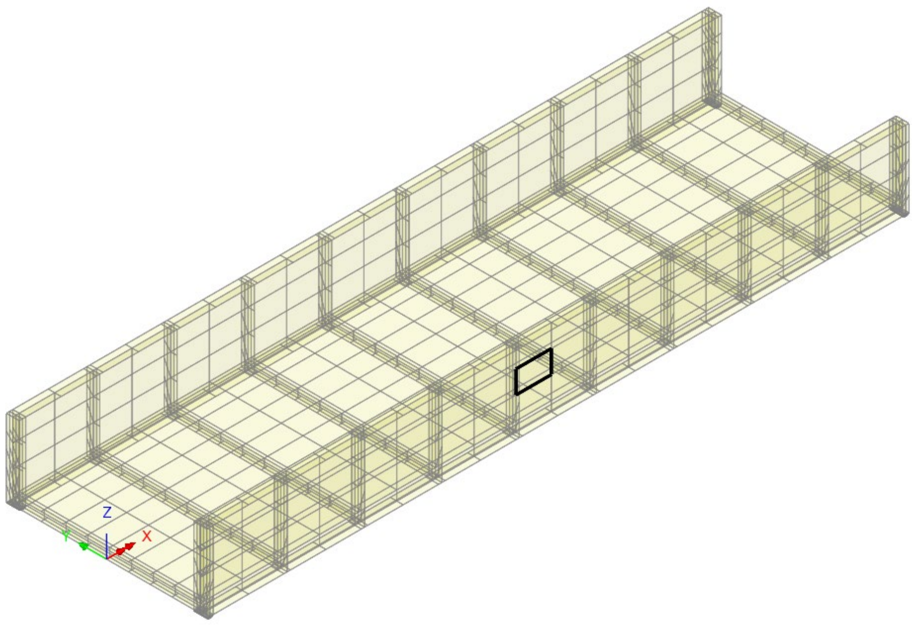
- Turn off the display of the **Deformed mesh** and **Annotation** layers in the Treeview.
- In the Treeview double-click on the **Mesh** layer name and click the **OK** button to accept the default settings. This will turn on the layer.

To view just the bridge structure without the ballast and track:

- In the Treeview click the right-hand mouse button on the group name **Bridge_Structure** and select the **Set as Only Visible** option from the drop-down menu.

By selecting or moving the cursor over the node and element shown, the node or element number of interest can be obtained. For the first stage of this analysis we are interested in the node at the centre of the bridge deck (node 1696) and the element in the middle of the side girder (element 1209), as shown in the following figures.


Z
Y
X


Z
Y
X

Defining the Eurocode ENV 1991-3 Type 3 Trainset

Before the analysis can be performed, we need to define the moving load representation of the Eurocode ENV 1991-3 Type 3 trainset in LUSAS Modeller.

Note. To simplify the use of IMDPlus (and provide an alternative to picking IMDPlus menu selections from the Analyses > IMDPlus menu items) for the rest of the example it is recommended that the IMDPlus toolbar is enabled in LUSAS Modeller.

- Select the **View** > **Toolbars...** menu item, select the **Toolbars** tab, enable the **IMDPlus** option in the list and click **Close**.

- If the IMDPlus toolbar has been enabled, click on the Moving Load analysis button in the toolbar to select a moving load analysis and enable the tool button shortcuts to the dialogs.

Analyses
IMDPlus >
Moving Load >
Vehicle Configuration...

This displays the Moving Load Vehicle Configuration dialog.

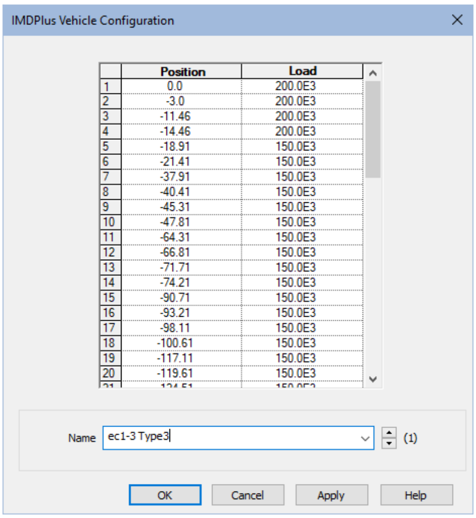
The moving load vehicle is to be defined using the positions of the axles relative to the front of train together with the moving load factors to be applied at each position. To simplify the definition of the vehicle the positions and loads are included in a Microsoft Excel spreadsheet so they can be copied and pasted into the dialog.

- Locate the spreadsheet named **ec1-3 Type3.xls** in the downloaded **\Lusas_associated_examples_files** folder and open it.

- Select all of the 60 positions and loads in the first and second columns and copy these to the clipboard using the **Ctrl+C** keys.

- In the Modeller dialog, select both the **Position** and **Load** headers of the grid in the dialog and paste the copied data into the grid using the **Ctrl+V** keys.

- Enter the name as **ec1-3 Type3**



Once finished the dialog should appear as shown.

- Click **OK** to create the vehicle configuration.

Note. The positions of the axles are defined as negative values to ensure that the whole trainset passes over the structure. Negative values place the axles behind the front of the train which is at a position of 0. The movement of the front of the train will be calculated from the start of the path to the end of the path with additional time included in the IMDPlus solution to allow all of the axles with negative positions to pass along the path.

If any axles are defined with positive values, then these will already be the distance down the path equivalent to the position entered in the vehicle configuration. Those axles with positive positions may already be over the structure at the start of the IMDPlus analysis if the start of the path has not been defined to account for this. If any positive positions are used, then always ensure that the lines defining the beginning of the path allow sufficient additional length in order to model the transition of the whole of the train onto the structure correctly.

Note. Once a trainset or vehicle has been defined it can be saved in a library so it can be imported and used in future analyses without the need to go through all of the definition process above. This is achieved through the **Library Browser** accessed through the **File > Import/Export Model Data...** menu command.

Importing a Vehicle

If it proves time consuming or you are unable to obtain the same results shown later in the example the vehicle definition can be imported from the library provided in the **\Lusas_associated_examples_files** folder.

- ❑ The **ec1-3 Type3.lmd** contains the vehicle library for the example.

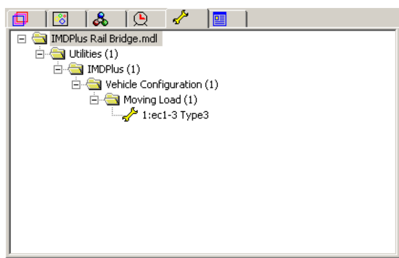
File
Import/Export Model Data…

- Select the **Import from library to model** option.

Click on the **Choose file...** button and browse to the **ec1-3 Type3.lmd** file in the **\Lusas_associated_examples_files** folder.

- Select the **IMDPlus (1)** entries in the tree.
- Click the **OK** button.

After vehicle configuration attribute has been defined it will appear in the Utilities treeview



Note. If it is required to edit the vehicle configuration attribute simply double-click with the left mouse button or right-click and choose **Edit Attribute...** on the name of the attribute to bring up the original dialog.

Moving Load Analysis

Moving load calculations are performed using the IMDPlus (Interactive Modal Dynamics) facility. In order to carry out the moving load analysis of the train travelling across the bridge we need to carry out three stages:

1. Define and set-up the path along which the moving loads will travel using a unit load defined as either a discrete point or patch load. For this example the unit axle load has already been defined as a discrete point load called **Unit Axle Load** which acts vertically
2. Convert the loading along this path from this unit load into modal forces that are applied in the IMDPlus moving load analysis.
3. Run an IMDPlus moving load analysis to calculate the response of the bridge.

Note. This process is similar to the IMDPlus moving mass analysis procedure but with the trainset / vehicle defined by constant forces rather than spring-mass systems.

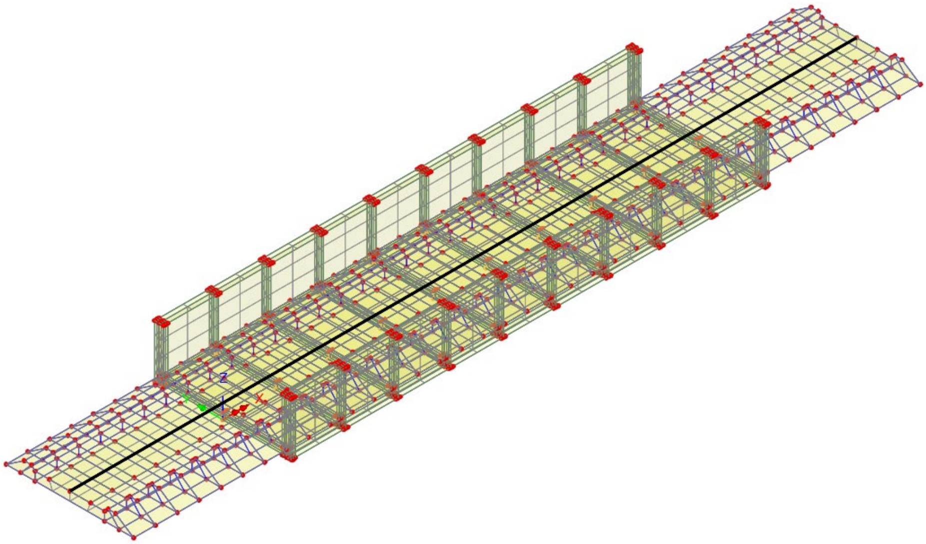
Note. Before an IMDPlus analysis can be carried out the load that is going to pass over the structure must be defined using either discrete point or patch loads. For this example this has already been carried out with a single axle of unit load defined as a discrete point load. Defining a single axle allows multiple load configurations to be analysed through the composite axle definition method in IMDPlus without the need to carry out the path and modal force stages for each layout. For railways the axle lengths remain constant over all of the train set and this method would normally be used. For moving loads where axles are of different widths the full definition of the load must be carried out with the path and modal force stages carried out for each layout.

Defining the Moving Load Path

To solve for the passage of the train across the bridge the path for the moving load must be defined. Line 12000 (the line representing the path of the moving load) will be set to be the current selection.

To view the complete model again:

- In the Treeview click the right-hand mouse button on the group name **IMDPlus Rail Bridge.mdl** and select the **Visible** option from the drop-down menu. Click **Yes** when asked whether to act on subgroups as well.
- In the Treeview double-click on the **Geometry** layer name and click the **OK** button to accept the default settings. This will also turn on the layer.
- Select the **line** shown (line 12000)



Note. The path can be built from multiple lines and arcs but these must form a continuous path without branching.

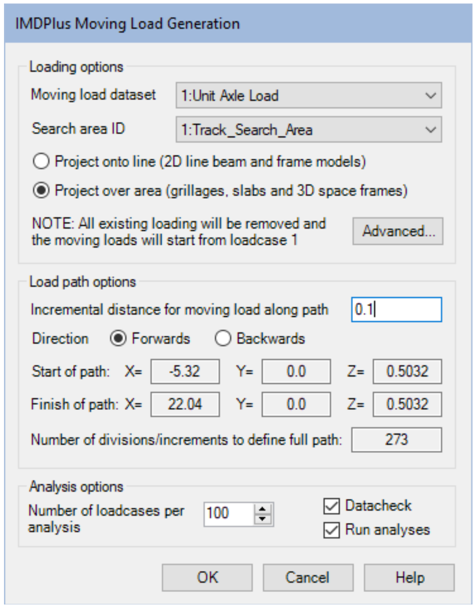
Analyses
IMDPlus >
Moving Load >
Moving Load Generation...

This opens the IMDPlus Moving Load Generation dialog.

On startup of the IMDPlus Moving Load Generation dialog, all valid discrete loads and search areas will be made available in the loading options along with information about the path defined by the current selection.

In this example a single discrete load called Unit Axle Load which defines the unit loading from a single axle of the train is present along with a search area that is assigned to the weak weightless shells.

- Ensure **1:Unit Axle Load** is selected from the **Moving load dataset** list.
- Ensure **1:Track_Search_Area** is selected from the **Search area ID** for the assignment of the discrete loading.
- Ensure **Project over area** is selected.
- Click on the **Advanced** button to adjust the inclusion of load characteristics. On the Moving Load Advanced Options dialog choose the **Include full load** option for loads outside the search area and click the **OK** button.
- On the IMDPlus Moving Load Generation dialog set the **Incremental distance** to **0.1**



Note. Using search areas targets the application of the loading to the required features as described in the Modeller Reference Manual.

Note. By default the incremental distance is set to one tenth of the length of the line along which the load moves.

- Click the **OK** button to proceed and choose **Yes** to accept the warnings and save the current model.

The program will now generate the loading information for the 274 locations of the unit axle along the path before returning control back to LUSAS Modeller. This process does not need to be repeated unless the lateral configuration of the load changes. For a railway this will not happen, but it may be required for highway analyses where the axle lengths and tyre configurations could vary.

Note. The discrete loading locations defined by this dialog will be tabulated into three datafiles with a maximum of 100 loadcases each and the analyses will be performed automatically. These analyses will use the same file basename as the original model with a numeric indicator appended to it (e.g. _00001, _00002, etc). They are required for the modal force calculation stage.

Generating the Modal Force History for the Moving Load

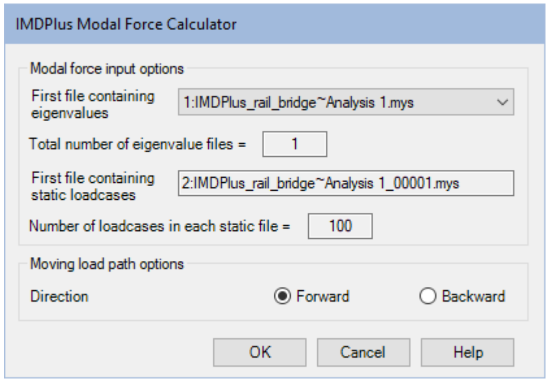
In the previous stage the passage of the train axle across the structure has been defined. The modal forces for the IMDPlus solution now need to be calculated using the Modal Force Calculator.

Analyses
IMDPlus >
Moving Load >
Modal Force Calculator...

This opens the IMDPlus Modal Force Calculator dialog.

- Click the **OK** button to accept the default information and proceed.

Note. This process does not need to be repeated unless the moving load path or configuration in Stage 1 is changed.

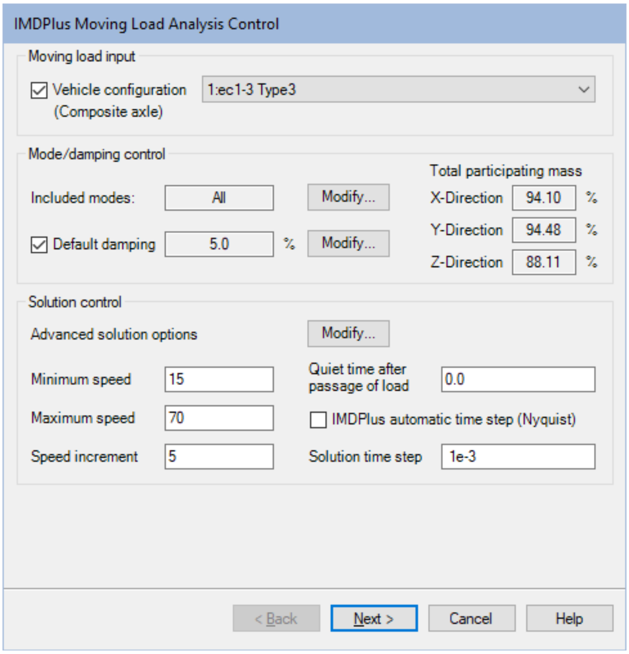


Defining the Moving Load Parameters

All of the basic moving load information has now been defined for the IMDPlus analysis. The next stage is to define the included modes, damping and speed parameters.

Analyses
IMDPlus >
Moving Load >
Moving Load Analysis...

This opens the IMDPlus Moving Load Analysis Control dialog.



- Click on the **Vehicle Configuration (Composite axle)** option since we are using a unit load axle definition.

- Ensure the Vehicle configuration contains **1:ec1-3 Type3**

- Ensure that **Included modes** is set to **All**. If this is not the case, click on the **Modify…** button and ensure the **All modes** option is selected.

- Ensure **Default damping** of **5.0** is selected. If a different damping is displayed, click on the **Modify…** button and set the **Default damping** to **5.0**

- In the Solution control section, click on the **Modify...** button to change the advanced solution options. Click the **Defaults** button to set the default options and click the **OK** button.

- Enter the **Minimum Speed** as **15**, the **Maximum Speed** as **70** and the **Speed Increment** as **5**

- Deselect the **IMDPlus determining time step (Nyquist)** option so we can specify the required time step

- Enter the **Solution time step** as **1E-3**

- Click the **Next** button to proceed. When prompted about significant missing total mass choose **Yes** to continue. For this analysis we are only interested in the contributions of modes of vibration up to and including 35Hz which means that we are not going to achieve the 90% total mass target.

The information entered above will analyse the passage of a Eurocode ENV 1991-3 Type 3 train (with axle details as held in the file ec1-3 Type3.xls) across the bridge for a speed range of 15 m/s to 70 m/s in increments of 5 m/s (or 54 kph to 252 kph in increments of 18 kph). The quiet time allows for the decay of the response of the bridge after the train has passed across and the solution time step forces the time step to be used in the analyses.

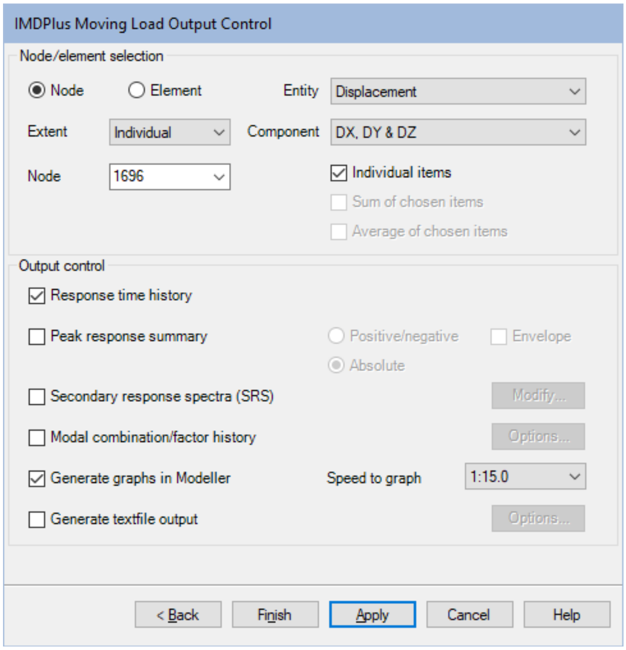
Displaying Individual Node and Element Results for Moving Load Analysis

The IMDPlus Output Control dialog will appear. This controls the results output for the model.

Displacement and Acceleration Graphs

The response of the mid-span of the bridge for the range of speeds selected will be investigated. Initially we will look at the displacements of the mid-span for a single speed of 15 m/s (or 54 kph).

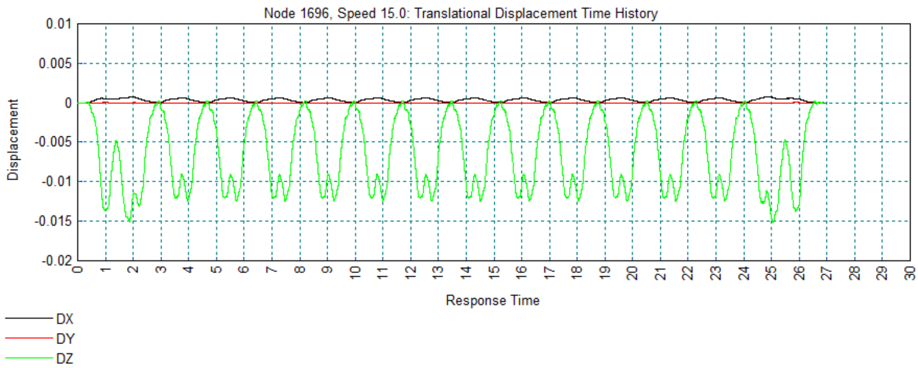
Enter the following information into the output control dialog:



- Choose **Node** and select **Extent** as **Individual**
- Enter **Node** number **1696** (This is the node in the centre of the bridge deck at the mid-span of the bridge)
- Select **Displacement** results of **DX, DY & DZ**
- Ensure **Individual items** is selected. **Sum of chosen items** and **Average of chosen items** will not be available as an individual node is being processed.
- Ensure **Response time history** is selected.
- Ensure **Generate graphs in Modeller** is selected.
- Ensure **Speed to graph** is set to be **1:15.0** which indicates that the first speed of 15 m/s is being processed.
- Click the **Apply** and not the Finish button to proceed.

Note. Clicking the Apply button instead of the Finish button keeps the IMDPlus Control Dialog accessible for subsequent graph plotting.

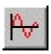
The IMDPlus analysis will now run.



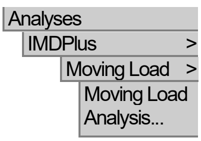
- After the graph has been displayed and viewed, close the graph

The vertical acceleration response of the mid-span for a single speed of 15 m/s (or 54 kph) will now be investigated.

If the IMDPlus toolbar has been enabled,

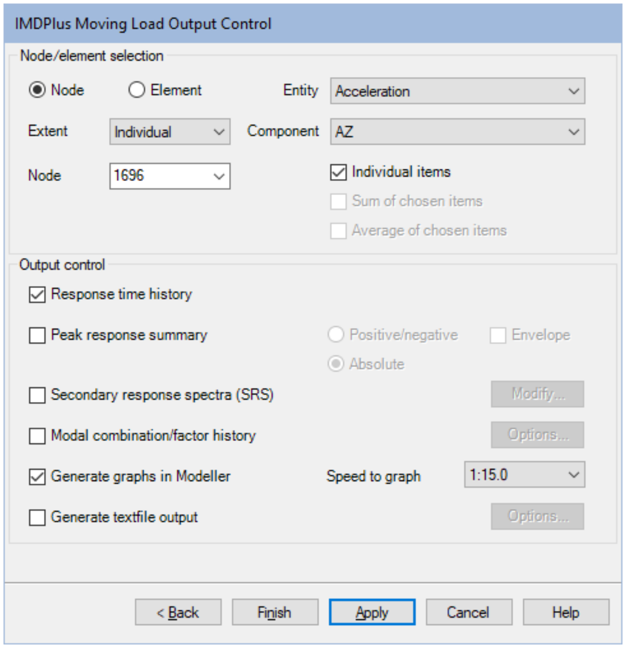
- Click on the  button in the toolbar to open the IMDPlus Output Control dialog

If the IMDPlus toolbar is not enabled,

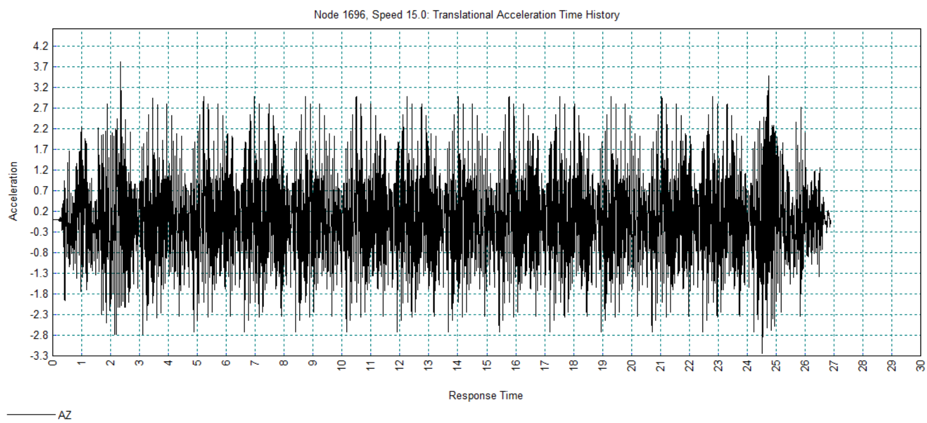


- Open the IMDPlus Moving Load Analysis Control dialog and click **Next >** to keep the existing analysis control settings and open the IMDPlus Output Control dialog.

- On the IMD Output Control dialog select **Acceleration** results of **AZ** for the vertical component only
- Click the **Apply** button and not the Finish button to proceed.



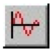
Note. IMDPlus does not need to be rerun since the acceleration results were computed at the same time as the displacement results.



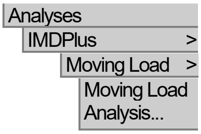
- When the graph has been displayed, close the graph

Previously we have investigated the displacement and acceleration response of the mid-span of the bridge deck for a single train speed. We will now look at the peak positive and negative vertical displacement and acceleration responses of the mid-span over the speed range of 15 m/s to 70 m/s as specified previously in the moving load analysis control dialog.

If the IMDPlus toolbar has been enabled,

- Click on the  button in the toolbar to open the IMDPlus Output Control dialog

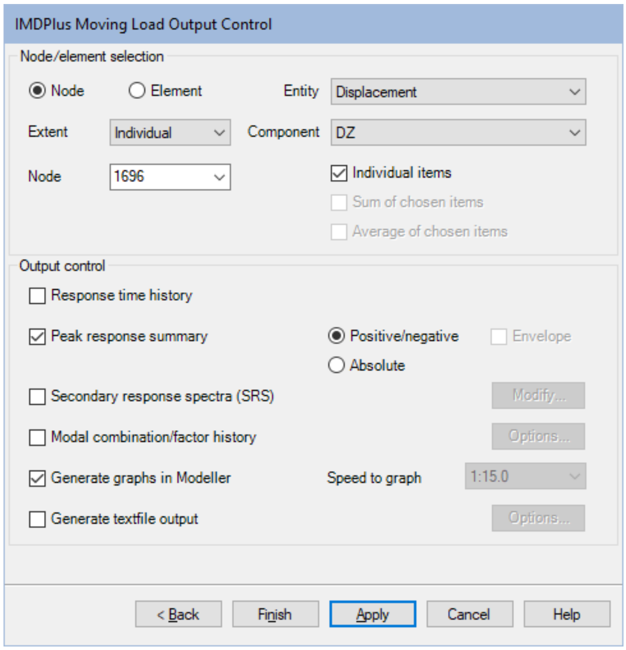
If the IMDPlus toolbar is not enabled,

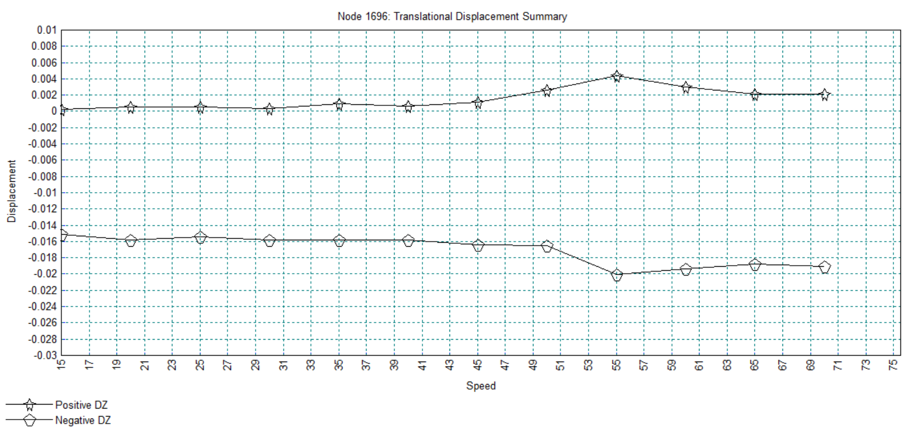


- Open the IMDPlus Moving Load Analysis Control dialog and click **Next >** to keep the existing analysis control settings and open the IMDPlus Output Control dialog.

- On the IMDPlus Output Control dialog select **Displacement** results of **DZ** for the vertical component only.
- Deselect the **Response time history** option.
- Select the **Peak response summary** option.
- Select **Positive/negative**
- Click the **Apply** button to proceed.

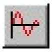
The IMDPlus analysis will now run.



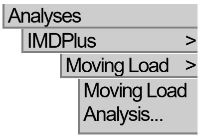


- When the graph has been displayed, close the graph.

If the IMDPlus toolbar has been enabled,

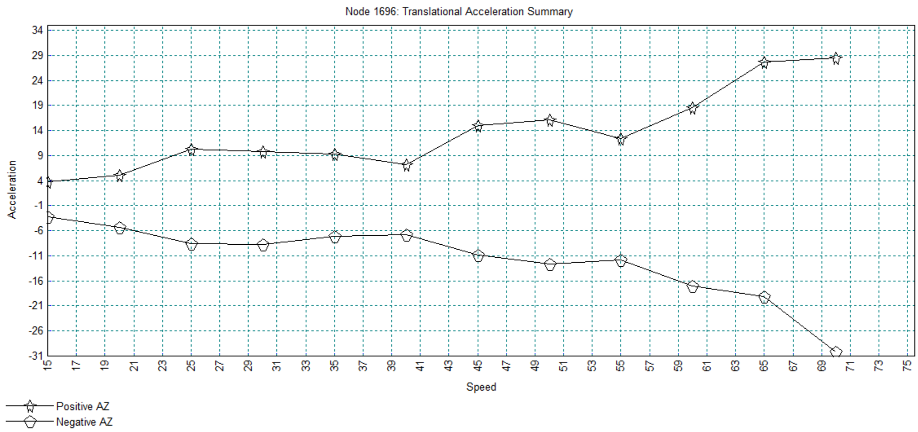
- Click on the  button in the toolbar to open the IMDPlus Output Control dialog.

If the IMDPlus toolbar is not enabled:



- Open the IMDPlus Moving Load Analysis Control dialog and click **Next >** to keep the existing analysis control settings and open the IMDPlus Output Control dialog.

- Select **Acceleration** results of **AZ** for the vertical component only
- Click the **Apply** button to display a graph of acceleration versus speed at the mid-span.

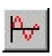


- When the graph has been displayed, close the graph

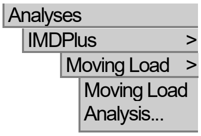
Stress Resultant Graphs for Shells

In the previous section the displacement and acceleration responses at the mid-span of the bridge were investigated. We will now look at the stress resultants in the web of one of the main girders. Results for element number 1209 in the centre of the web of the nearside girder (as previously determined) will be investigated.

If the IMDPlus toolbar has been enabled,

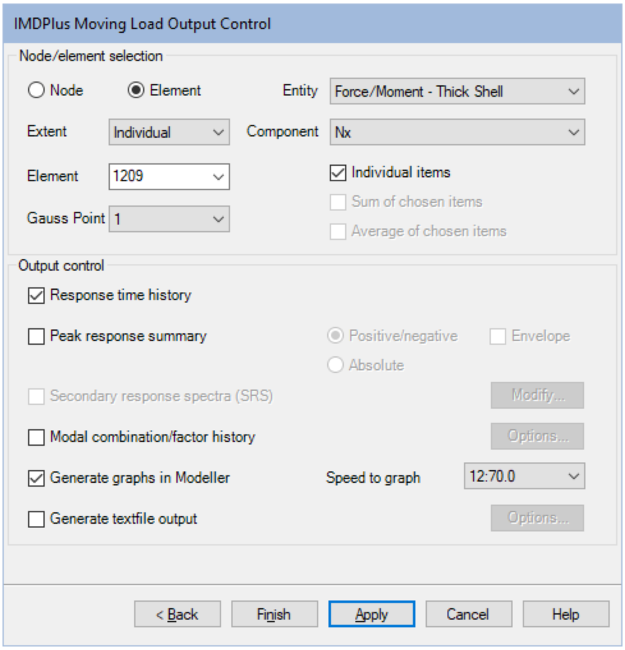
- Click on the  button in the toolbar to open the IMDPlus Output Control dialog

If the IMDPlus toolbar is not enabled:



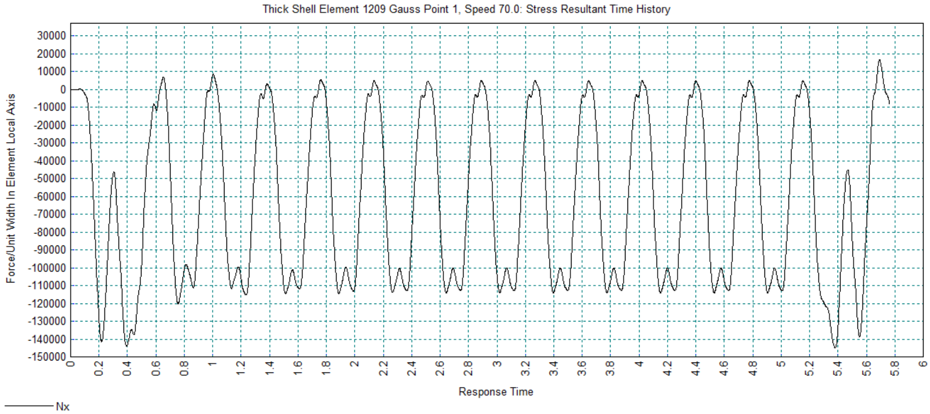
- Open the IMDPlus Moving Load Analysis Control dialog and click **Next >** to keep the existing analysis control settings and open the IMDPlus Output Control dialog.

Enter the following information into the IMDPlus Output Control dialog.



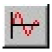
- Select **Element** and ensure **Extent** remains set as **Individual**
- Enter **Element** number **1209**
- Set **Gauss Point** to **1**
- Select **Force/Moment – Thick Shell** results of **Nx** which is the stress resultant in the longitudinal bridge direction.
- Ensure **Individual items** is selected. 'Sum of chosen items' and 'Average of chosen items' will not be available as an individual element is being processed.
- Ensure the **Response time history** option is selected.
- Deselect the **Peak response summary** option.
- Set the **Speed to graph** as **12:70.0** which indicates that the twelfth listed speed of 70 m/s is being processed.
- Click the **Apply** button to display a graph of Nx versus time for gauss point 1 of element 1209.

The IMDPlus analysis will now run and a graph of Nx versus time for gauss point 1 of element 1209 will be displayed.

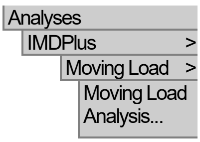


- When the graph has been displayed, close the graph

If the IMDPlus toolbar has been enabled,

- Click on the  button in the toolbar to open the IMDPlus Output Control dialog

If the IMDPlus toolbar is not enabled,

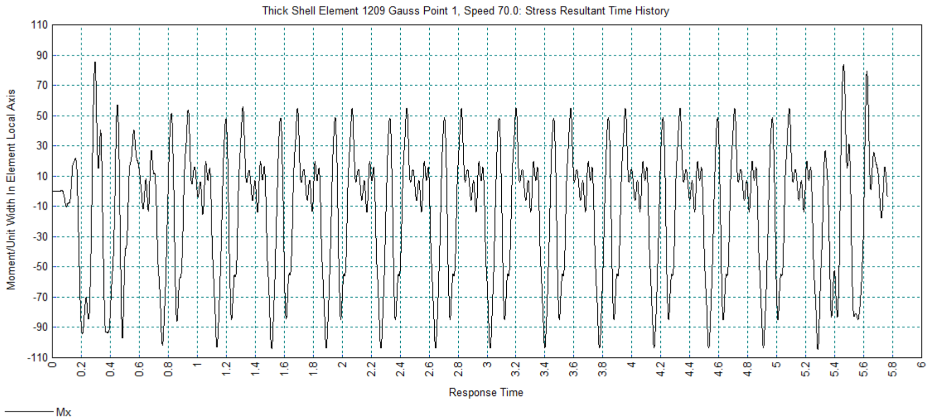


- Open the IMDPlus Moving Load Analysis Control dialog and click **Next >** to keep the existing analysis control settings and open the IMDPlus Output Control dialog.

- Select **Force/Moment – Thick Shell** results of **Mx** which is the moment in the along bridge direction.

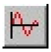
- Leaving all previous options set as they were, click the **Apply** button to proceed.

After a short pause a graph of Mx versus time for gauss point 1 of element 1209 will be created.

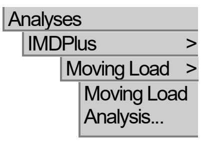


- When the graph has been displayed, close the graph

If the IMDPlus toolbar has been enabled,

- Click on the  button in the toolbar to open the IMDPlus Output Control dialog

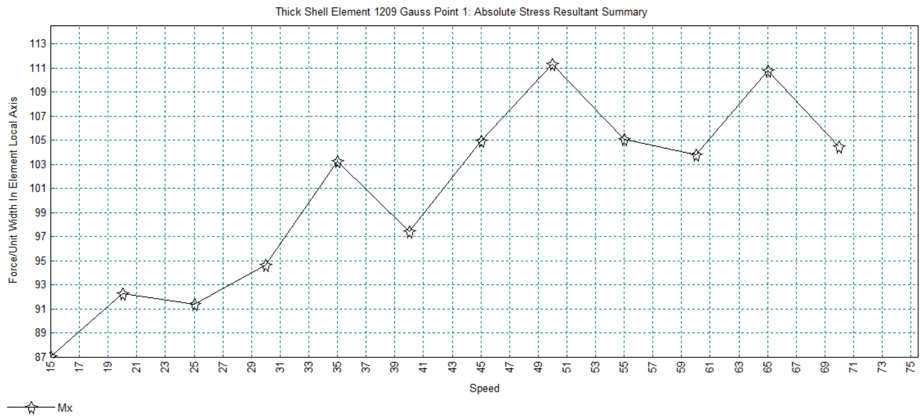
If the IMDPlus toolbar is not enabled,



- Open the IMDPlus Moving Load Analysis Control dialog and click **Next >** to keep the existing analysis control settings and open the IMDPlus Output Control dialog.

- Deselect the **Response time history** option.
- Select the **Peak response summary** option and select **Absolute**
- Click the **Finish** button.
- Click **Yes** when asked whether to free up disk space by deleting the temporary files created by IMDPlus.

A graph of absolute peak Mx versus speed for gauss point 1 of element 1209 will be generated.



- Close the graph window.

Displaying Results for a Selection of Nodes and Elements

In the preceding sections the analyses utilised individual nodes and elements of the structure. In the following sections chosen sets of nodes and elements will be used in order to investigate the following results for the bridge structure:

- ❑ Averaged and peak displacements and dynamic amplification factors
- ❑ Total summed reactions and peak reactions
- ❑ Averaged and peak stresses in a side panel

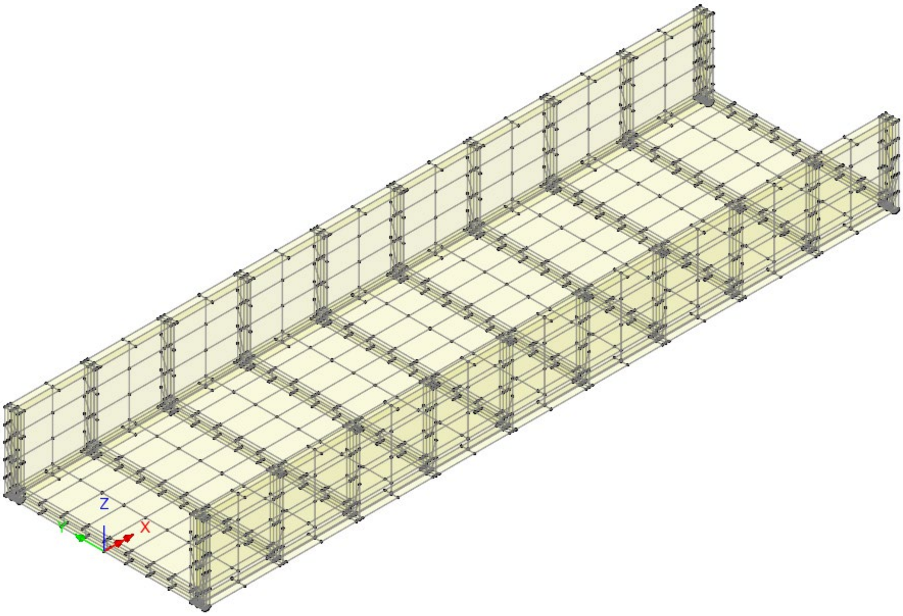
Averaged and Peak Displacements and Dynamic Amplification Factors for the Bridge Structure

In order to examine the averaged and peak displacements and dynamic amplification factors, a selection of nodes needs to be created that contains all of the nodes of the bridge structure.

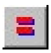
- Turn off the **Geometry** layer in the Treeview.

- In the Treeview click the right-hand mouse button on the group name **Bridge_Structure** and select the **Set as Only Visible** option from the drop-down menu.

Using Select Nodes drag a box around the model to select all of the 1665 nodes of the bridge structure, as shown in the following figure.

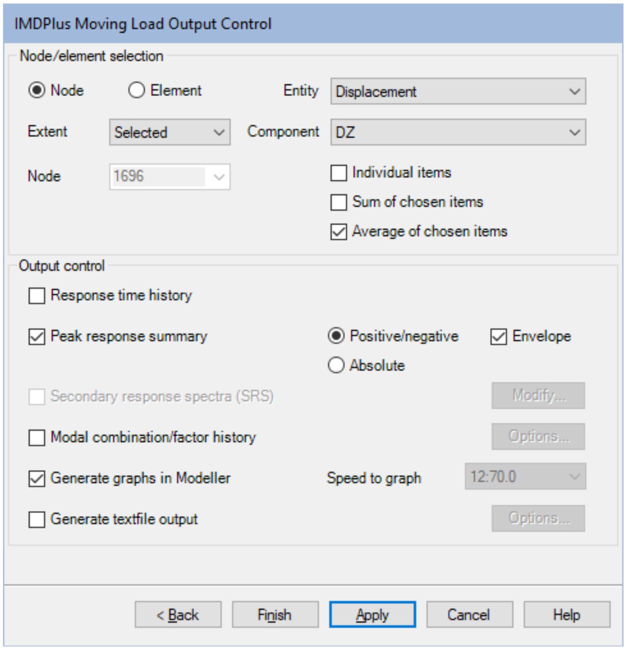


Analyses
IMDPlus >
Moving Load >
Moving Load Analysis...

- Open the IMDPlus Moving Load Analysis Control dialog through the menu or click on the  button in the toolbar.
- On the IMDPlus Moving Load Analysis Control dialog click the **Next** button to accept the previously defined values. When prompted about the total mass participation click the **Yes** button to continue.

Enter the following information into the IMDPlus Output Control dialog.

- Select **Node** and change **Extent** to **Selected** using the drop-down list. This chooses all 1665 nodes of the bridge structure that were selected in the preceding step.
- Select result entity **Displacement** and component **DZ**
- Deselect **Individual items**
- Select **Average of chosen items** as only the averaged results for the selected nodes are going to be investigated.



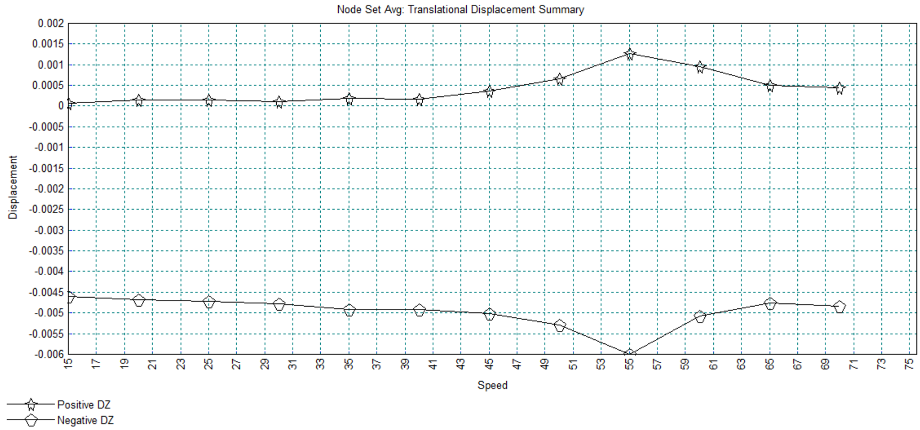
- Ensure **Peak response summary** remains selected, then select **Positive/negative** and **Envelope**
- Ensure **Generate graphs in Modeller** remains selected.
- Click the **Apply** button to perform the analysis. Click **Yes** when asked whether you want to process all of the selected nodes.

The IMDPlus analysis will now run. On modern computers this will take under 15 minutes.

Note. Any combination of the options **Individual items**, **Sum of chosen items** and **Average of chosen items output** can be used together in an IMDPlus analysis, although using the **Individual items** option when **Extent** is set to **Selected** or **All** (nodes or elements) may produce a large number of graphs, depending on the number of nodes or elements chosen for processing.

Note. **Average of chosen items** obtains results by first summing the results from the selected nodes. A simple average of this summed result is obtained to give the averaged node time histories from which the peak average results are obtained.

A graph of peak positive and negative results for the averaged vertical (DZ) displacements, for all of the speeds analysed, 15m/s to 70m/s, is displayed as shown in the following figure. From the adjacent tabbed data table, it can be seen that the largest peaks occur at a speed of 55m/s, with positive and negative peak values of 0.0013m and -0.006m respectively.



An envelope of the peak displacements and rotations for the selected nodes is displayed on screen in Notepad and written to the file **peak_dspSet1.sum** which can be found in the \LUSASFiles32\IMDPlus_rail_bridge\IMDPlus_Graphing folder.

By investigating all of the speeds analysed it can be seen that the individual peak vertical (DZ) displacements also occur at a moving load speed of 55m/s.

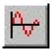
```
# +--------------------------+
# | Speed = 55.0000000000000 |
# +--------------------------+
#
# Entity                 Time            Value             Node
Peak_Pos_DX           6.807000000      0.3171215952E-002      1052
Peak_Neg_DX           6.815000000     -0.1438707644E-002      2416
Peak_Pos_DY           6.830000000      0.1429801729E-001      1641
Peak_Neg_DY           6.834000000     -0.1430789598E-001      1720
Peak_Pos_DZ           4.656000000      0.4399301289E-002      1648
Peak_Neg_DZ           6.826000000     -0.2032896221E-001      1648
Peak_Pos_THX          6.837000000      0.1274026641E-001      1718
Peak_Neg_THX          6.837000000     -0.1267684300E-001      1697
Peak_Pos_THY          6.974000000      0.5644280262E-002       974
Peak_Neg_THY          0.5750000000    -0.6119502396E-002      2309
Peak_Pos_THZ          0.4680000000     0.4478363560E-002      1885
Peak_Neg_THZ          7.150000000     -0.4301679976E-002      2301
#
```

Both positive and negative peak Z-displacements occur at node 1648 with respective values of 0.0044m at time 4.656 seconds and -0.0203m at time 6.826 seconds.

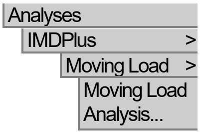
Note. The envelope of the peak results is obtained in IMDPlus by examining the individual results from all of the nodes in the bridge structure. This enables the locations of the nodes with maximum and minimum results to be quickly identified.

- Close the Notepad application and graph windows.

If the IMDPlus toolbar has been enabled,

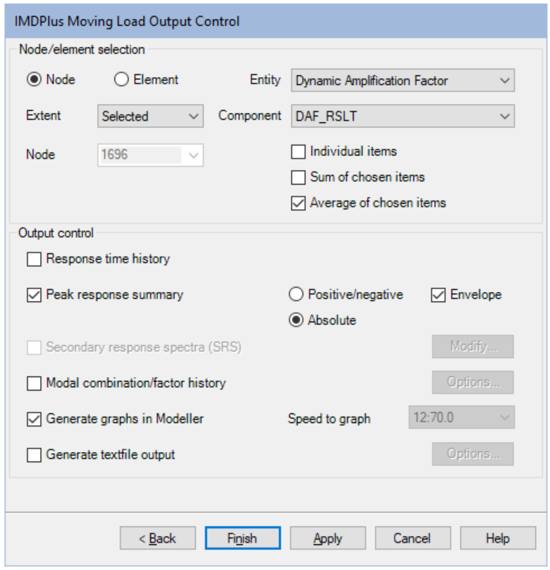
- Click on the  button in the toolbar to open the IMDPlus Output Control dialog

If the IMDPlus toolbar is not enabled,



- Open the IMDPlus Moving Load Analysis Control dialog and click **Next >** to keep the existing analysis control settings and open the IMDPlus Output Control dialog.

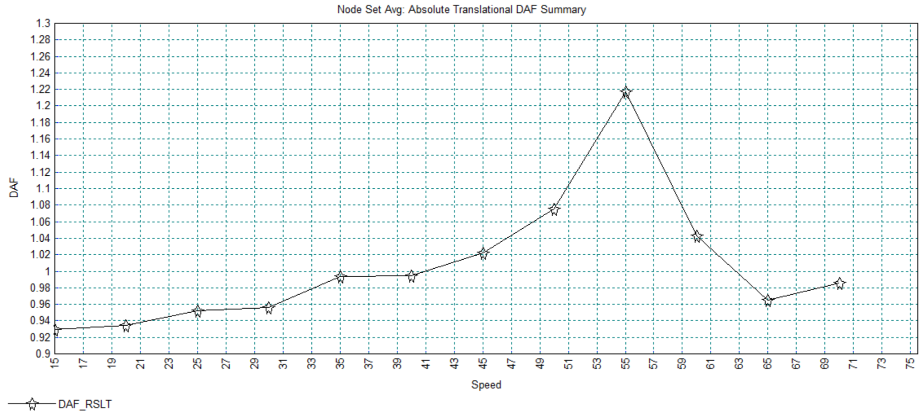
Enter the following information into the IMDPlus Output Control dialog.



- Ensure **Node** and extent **Selected** are chosen.
- Select result entity **Dynamic Amplification Factor** and component **DAF_RSLT**
- Ensure **Average of chosen items** is selected.
- Ensure **Peak response summary** and **Envelope** remain selected and select **Absolute**
- Click the **Finish** button. Click **Yes** when asked whether you want to process all of the selected nodes.
- Click **Yes** when asked whether to free up disk space by deleting the temporary files created by IMDPlus.

A graph showing the absolute peak of the average resultant dynamic amplification factor against speed is displayed, as shown in the following figure. From the adjacent tabbed data table, this shows that a maximum averaged DAF of 1.217 occurs at speed 55m/s.

Note. Only averaged dynamic amplification factor results can be obtained for a set of nodes as summed results are meaningless for this result entity.



An envelope of the peak dynamic amplification factors for the selected nodes is displayed on screen in Notepad and written to the **Abs_peak_dafSet1.sum** which can be found in the \LUSASFiles32\IMDPlus_rail_bridge\IMDPlus_Graphing folder.

```
#
# +-------------------------+
# | Speed = 60.0000000000000 |
# +-------------------------+
#
# Entity                   Time           Value            Node
Abs_Peak_DAF_DX         6.284000000     1.923285713        1081
Abs_Peak_DAF_DY        0.6700000000     2.913361939        1761
Abs_Peak_DAF_DZ        0.5310000000     1.702843564          16
Abs_Peak_DAF_THX       0.6710000000     6.930650787        2161
Abs_Peak_DAF_THY        6.351000000     1.646075290        1320
Abs_Peak_DAF_THZ       0.5850000000     2.616078282        1136
Abs_Peak_RSLT          0.5310000000     1.758098852          41
#
```

These results indicate that the individual peak resultant DAF occurs at a speed of 60m/s. A value of 1.76 is calculated at a solution time of 0.53 seconds at node 41.

- Close the Notepad application and graph window.

Total and Peak Reactions for the Bridge Structure

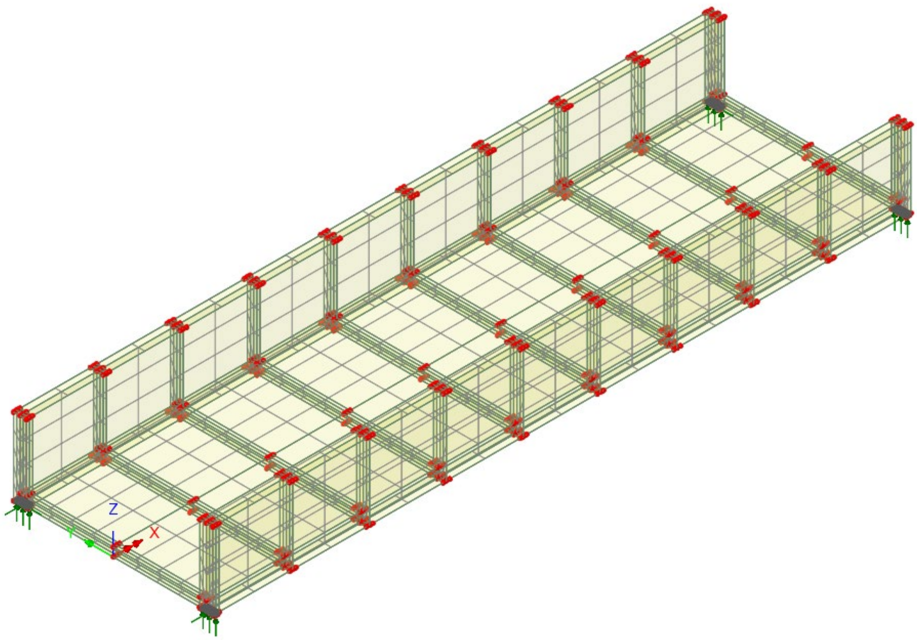
The total sum of the reactions and the peak reactions that act on the bridge structure for each of the moving load speeds will now be investigated. The set of nodes from the preceding section could be utilised for this purpose. However, in order to improve the efficiency of the IMDPlus solution, the chosen selection of nodes will be reduced so that it only includes the geometric features that contain the supported nodes of the bridge structure.

- Click the left-hand mouse button in a blank part of the view window to remove the node selection created in the preceding section.

In the LUSAS view window click on the Supports on/off button to show the supported nodes in the model.

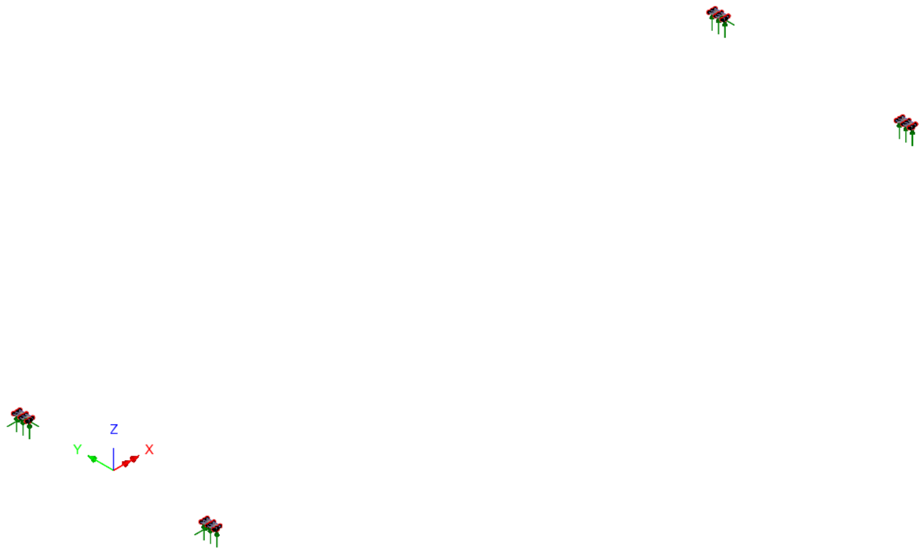
- In the Treeview click the right-hand mouse button on the group name **Bridge_Structure** and select the **Set as Only Visible** option from the drop-down menu.
- Turn on the **Geometry** layer in the Treeview.

Using the **Select Volumes** cursor drag a box around the entire bridge structure to select the volumes immediately above the bridge supports, as shown in the following figure.



- Click the right-hand mouse button in a blank part of the view window and select the **Keep as Only Visible** option. Only the selected volumes will remain visible.

  Using the **Select Nodes** cursor drag a box to select the 120 visible nodes of the bridge structure, as shown in the following figure.



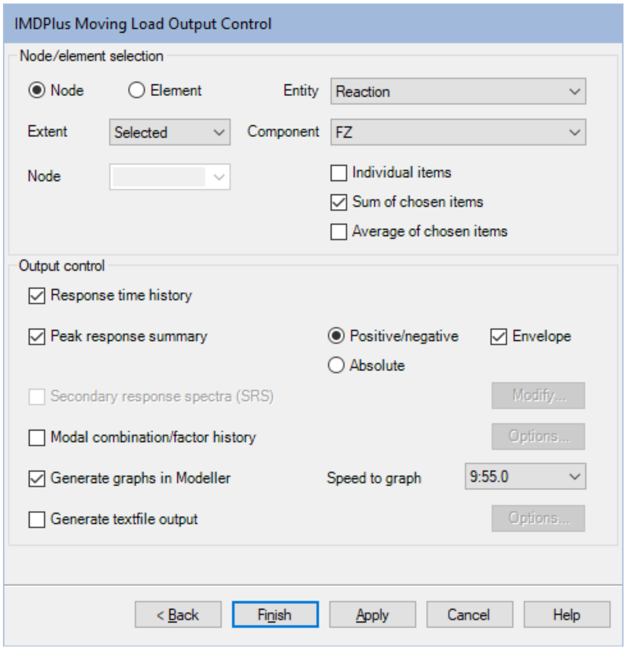
Analyses
IMDPlus >
Moving Load >
Moving Load Analysis...

Open the IMDPlus Moving Load Analysis Control dialog.

- Click the **Next** button to accept the previously defined values. When prompted about the total mass participation click the **Yes** button to continue.

- Enter the following information into the IMDPlus Output Control dialog.

- Select **Node** and ensure **Extent** remains set to **Selected**. This chooses the 120 visible nodes of the bridge structure that were selected in the preceding step.
- Select result entity **Reaction** and component **FZ**
- Deselect **Average of chosen items**
- Select **Sum of chosen items**. Ensure **Individual items** remains deselected.
- Select **Response time history**



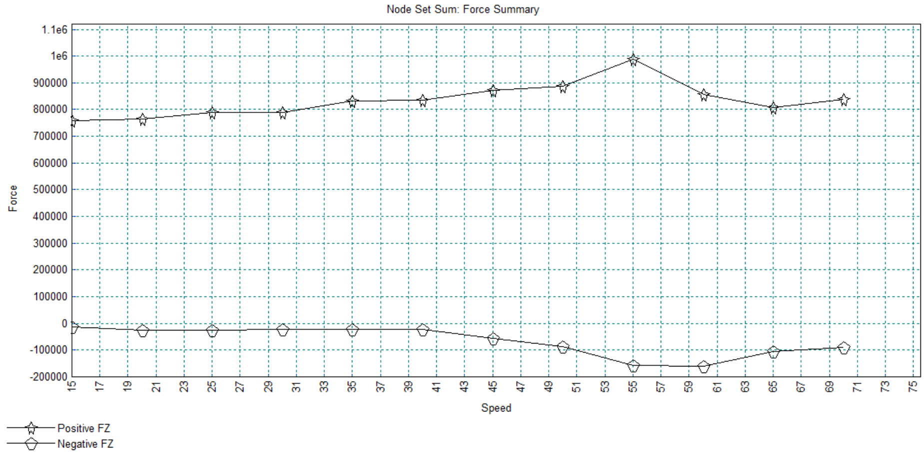
- Ensure **Peak response summary** and **Envelope** remains selected and select **Positive/negative**
- Ensure **Generate graphs in Modeller** remains selected.
- Set the **Speed to graph** as **9:55.0** which indicates that the ninth listed speed of 55 m/s is being processed.
- Click the **Finish** button to perform the analysis of the node set. Click **Yes** when asked whether you want to process all of the selected nodes.
- Click **Yes** when asked whether to free up disk space by deleting the temporary files created by IMDPlus.

Note. Sum of chosen items adds together the results from the selected nodes to give the summed nodal time histories from which the peaks of the summed results are obtained.

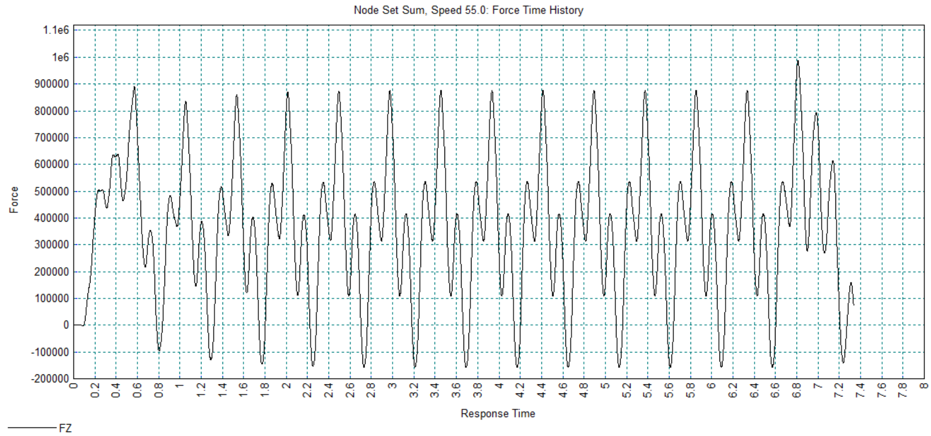
Note. Average of chosen items obtains results by first summing the results from the selected nodes. A simple average of this summed result is obtained to give the averaged node time histories from which the peak average results are obtained.

The summed nodal results that give the total vertical reactions acting on the bridge structure are displayed. The graph of the peak positive and negative summed reaction in the Z-direction for all of the speeds analysed is shown in the following figure.

From the adjacent tabbed data table, examining the results for each speed shows a positive peak reaction of 986.8kN at a train speed of 55m/s and a negative holding down peak reaction of -161.3kN at a speed of 60 m/s.



In addition, accessible form the Window menu item, the following figure shows the time history of the summed FZ reactions for the analysis speed of 55m/s. From the graph data for this speed it can be seen that the positive peak value of 986.8kN occurs at an analysis time of 6.812 seconds.



The envelope of the peak reactions from file **peak_rctSet1.sum** are displayed in a Notepad application. These give a summary of the peak reactions obtained from all of the individual nodes of the bridge structure for each of the moving load speeds analysed. The vertical (FZ) component of interest shows consistently that the maximum positive reaction (from a downward force) occurs at node 82 and the maximum negative reaction (from an upward force) occurs at node 74. Results for speeds of 55m/s and 60m/s are shown in the following figure.

```
#
# +-------------------------+
# | Speed = 55.0000000000000 |
# +-------------------------+
#
# Entity              Time          Value          Node
Peak_Pos_FX        6.756000000    51590.11153       10
Peak_Neg_FX        4.576000000   -18943.56117       10
Peak_Pos_FY        7.020000000    20253.47239       82
Peak_Neg_FY        6.996000000   -17812.56105       10
Peak_Pos_FZ       0.5750000000    215646.8013       82
Peak_Neg_FZ        6.944000000   -139145.0325       74
Peak_Pos_MX            N/A            N/A          N/A
Peak_Neg_MX            N/A            N/A          N/A
Peak_Pos_MY            N/A            N/A          N/A
Peak_Neg_MY            N/A            N/A          N/A
Peak_Pos_MZ            N/A            N/A          N/A
Peak_Neg_MZ            N/A            N/A          N/A
#
#
# +-------------------------+
# | Speed = 60.0000000000000 |
# +-------------------------+
#
# Entity              Time          Value          Node
Peak_Pos_FX        6.195000000    47446.85974       10
Peak_Neg_FX       0.6970000000   -16327.48305       10
Peak_Pos_FY       0.6720000000    20991.32218       10
Peak_Neg_FY       0.7020000000   -19540.90538       10
Peak_Pos_FZ       0.5330000000    211903.9209       82
Peak_Neg_FZ        6.368000000   -146751.0992       74
Peak_Pos_MX            N/A            N/A          N/A
Peak_Neg_MX            N/A            N/A          N/A
Peak_Pos_MY            N/A            N/A          N/A
Peak_Neg_MY            N/A            N/A          N/A
Peak_Pos_MZ            N/A            N/A          N/A
Peak_Neg_MZ            N/A            N/A          N/A
#
```

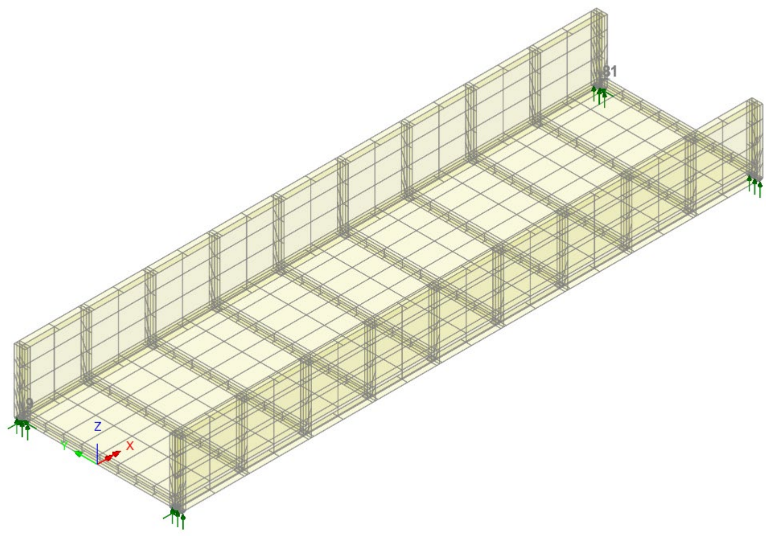
From the above data, the maximum positive reaction of 215.6kN is seen to occur at a time 0.575 seconds for speed 55m/s and the maximum negative reaction of -146.7kN occurs at a time 6.368 seconds for speed 60m/s.

- Close the Notepad application and graph windows.

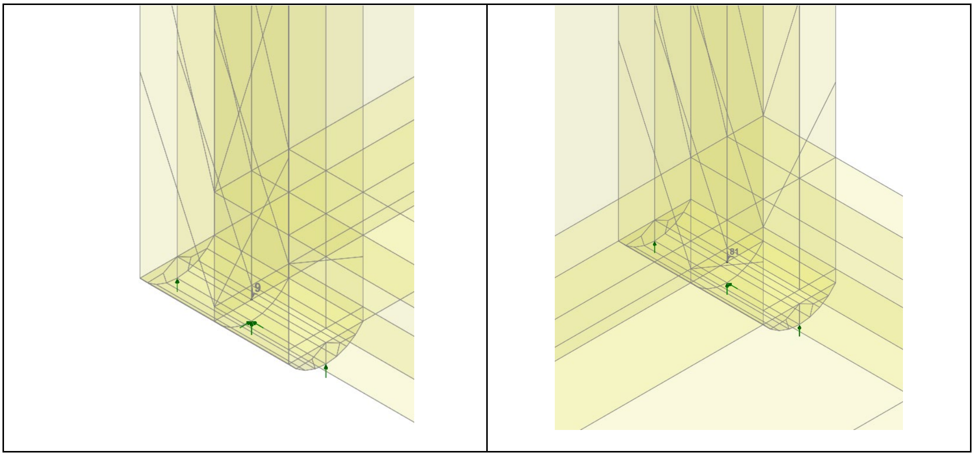
The nodes 81 and 9 representing the location of two of the vertical supports for the bearings of the bridge will now be selected in the model.

- Click the left-hand mouse button in a blank part of the view window to remove the node selection created in the preceding section.
- In the Treeview click the right-hand mouse button on the group name **Bridge_Structure** and select the **Set as Only Visible** option from the drop-down menu.
- Turn off the **Geometry** layer in the Treeview.

- With no features selected click the right-hand mouse button in a blank part of the view window and select the **Labels** option to add the labels to the Treeview.
- On the Properties dialog select the **Node / Name** and **Label selected items only** check boxes.
- Click the **Advanced...** button, then click the **Font…** button and select **Arial, Bold, 12** and click **OK.**
- Click the **OK** button as necessary to accept all other settings. This will turn on the layer in the view window.
- With no features selected click the right-hand mouse button in a blank part of the view window and select the **Advanced Selection...** option.
- Select **Type and Name**, select **Node** from the drop-down list and enter node number **81**
- Select **Add to selection** and click the **Apply** button to accept all other settings. Node 81 will be highlighted in the view window.
- Enter node number **9** and click the **OK** button. Node 9 will also be displayed in the view window, as shown in the following figure.



The node locations chosen are shown below for clarity.



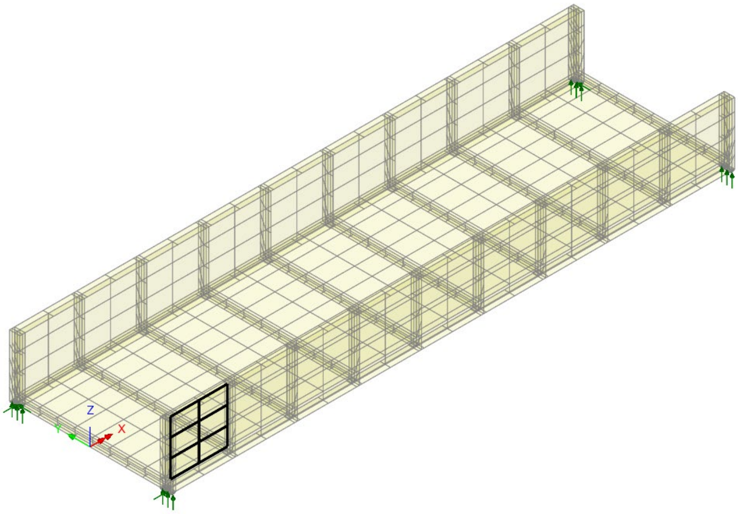
- Click the left-hand mouse button in a blank part of the view window to remove the node selection.

Average and Peak Stresses in a Side Panel of the Bridge Structure

Finally, the average peak and total peak in-plane shear stresses in a side panel of the bridge structure will be investigated.

- Double-click on the **Labels** layer name in the Treeview.
- On the Properties dialog deselect the **Node / Name** check box and select the **Element / Name** check box. Click the **OK** button.

Using the **Select Elements** cursor, select the six elements that form the side panel of the bridge structure, as shown in the following figure.



Note. Only elements of the same type, for example, thick beam elements, continuum elements or thick shell elements can be used in a set of IMDPlus elements. However, the element set may contain elements with different numbers of Gauss points or nodes.

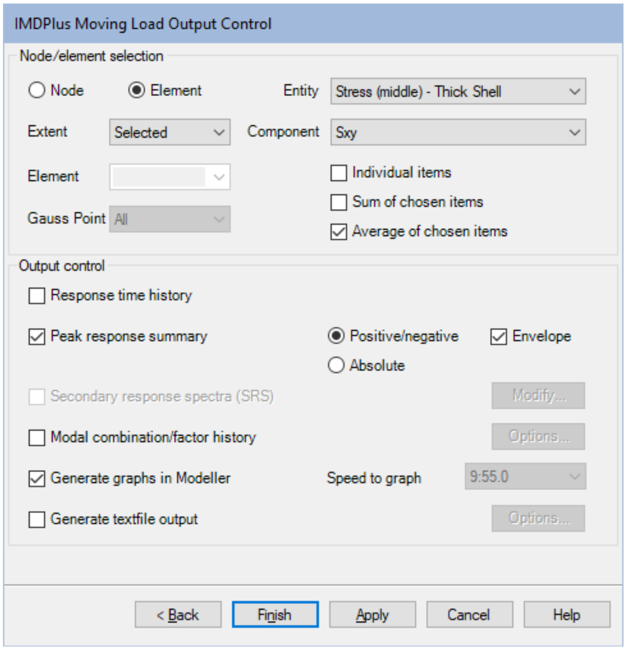
Analyses
IMDPlus >
Moving Load >
Moving Load Analysis...

Open the IMDPlus Moving Load Analysis Control dialog.

- Click the **Next** button to accept the previously defined values. When prompted about the total mass participation click the **Yes** button to continue.

Enter the following information into the IMDPlus Output Control dialog.

- Select **Element** and set **Extent** to **Selected** from the drop-down list. This chooses the 6 elements of the bridge structure that were selected in the preceding step.
- Select result entity **Stress (middle) – Thick Shell** and component **Sxy**
- <u>Deselect</u> **Sum of chosen items** and select **Average of chosen items**.
- Ensure **Individual Items** remains deselected.

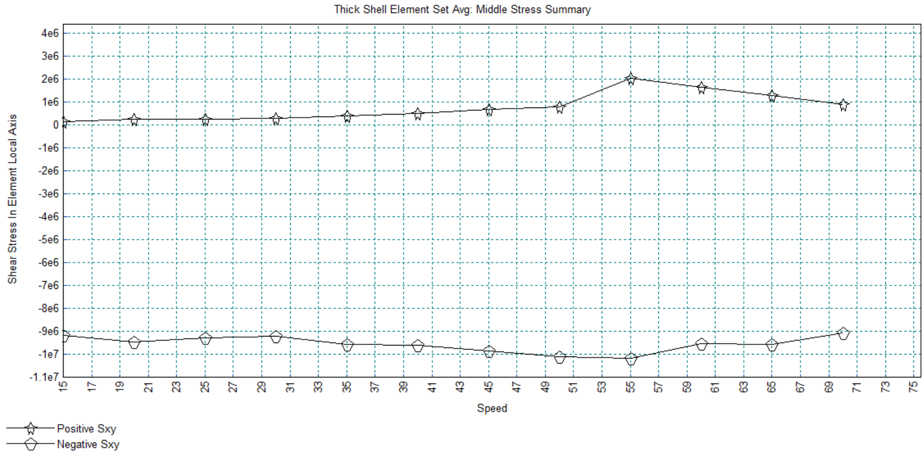


- <u>Deselect</u> **Response time history**
- Ensure **Peak response summary**, **Positive/negative** and **Envelope** all remain selected.
- Ensure **Generate graphs in Modeller** remains selected.

Note. As **Extent** has been set to **Selected** the drop-down lists **Element** and **Gauss Point** are not available for selection. In addition the element **Gauss Point** is automatically set to **All** as multiple elements are going to be processed in a single analysis.

- Click the **Finish** button to perform the analysis of the element set. Click **Yes** when asked whether you want to process all of the selected elements.
- Click **Yes** when asked whether to free up disk space by deleting the temporary files created by IMDPlus.

The graph shown in the following figure is displayed. It shows the peak positive and negative, average middle shear stress, Sxy, for the side panel of the bridge structure.



From the associated graph data table, the largest positive and negative peaks are seen to occur at a speed of 55m/s with values of 2.03Mpa and -10.2MPa respectively.

Note. The option **Average of chosen items** obtains the element results by first summing the results from all of the Gauss points of the selected thick shell elements. A simple average of these summed results is obtained to give the average element response time histories from which the peak average results are obtained.

An envelope of the peak element stresses for each of the moving load speeds is displayed in Notepad in file **peak_stressSet1.sum**. This gives a summary of the peak stresses and stress resultants obtained by examining all of the individual Gauss point results of the selected elements. The results for speed 55m/s are shown in the following figure.

```
# +--------------------------+
# | Speed = 55.0000000000000 |
# +--------------------------+
#
# Entity                  Time          Value             Element         GP
Peak_Pos_Top_Sx         6.804000000     6187041.778         576            1
Peak_Neg_Top_Sx         6.981000000    -17621080.12         580            4
Peak_Pos_Top_Sy         6.812000000     3221800.463         576            1
Peak_Neg_Top_Sy         6.796000000    -5296186.790         575            4
Peak_Pos_Top_Sxy        7.224000000     2729271.153         576            3
Peak_Neg_Top_Sxy        6.806000000    -11777411.04         575            2
Peak_Pos_Top_Syz        6.814000000     0.3074647326E-024   575            1
Peak_Neg_Top_Syz        7.226000000    -0.5699439799E-025   575            1
Peak_Pos_Top_Szx        6.822000000     0.1184384610E-023   575            1
Peak_Neg_Top_Szx        4.657000000    -0.2941288177E-024   575            1
Peak_Pos_Mid_Sx         6.985000000     5642834.400         576            2
Peak_Neg_Mid_Sx         6.986000000    -16293797.61         580            4
Peak_Pos_Mid_Sy         6.980000000     3211042.810         576            2
Peak_Neg_Mid_Sy         6.795000000    -5487373.279         575            4
Peak_Pos_Mid_Sxy        7.224000000     2668771.837         576            2
Peak_Neg_Mid_Sxy        6.798000000    -13599451.44         576            2
Peak_Pos_Mid_Syz       0.1350000000     233736.1969         576            2
Peak_Neg_Mid_Syz        6.914000000    -224229.0984         578            2
Peak_Pos_Mid_Szx        6.815000000     332154.0659         576            1
Peak_Neg_Mid_Szx        6.914000000    -326769.8170         576            1
Peak_Pos_Bot_Sx         6.980000000     6368749.644         576            2
Peak_Neg_Bot_Sx         6.803000000    -16530593.84         580            4
Peak_Pos_Bot_Sy        0.3340000000     4184517.673         578            2
Peak_Neg_Bot_Sy         6.980000000    -5974317.435         575            4
Peak_Pos_Bot_Sxy        7.223000000     3122244.381         575            2
Peak_Neg_Bot_Sxy        6.800000000    -16184421.24         576            2
Peak_Pos_Bot_Syz        6.814000000     0.6235161937E-024   575            1
Peak_Neg_Bot_Syz        4.653000000    -0.1001601270E-024   575            1
Peak_Pos_Bot_Szx        6.781000000     0.6470585098E-024   575            1
Peak_Neg_Bot_Szx        7.210000000    -0.1744639957E-024   575            1
Peak_Pos_Nx             6.985000000     71663.99688         576            2
Peak_Neg_Nx             6.986000000    -206931.2296         580            4
Peak_Pos_Ny             6.980000000     40780.24369         576            2
Peak_Neg_Ny             6.795000000    -69689.64064         575            4
Peak_Pos_Nxy            7.224000000     33893.40233         576            2
Peak_Neg_Nxy            6.798000000    -172713.0333         576            2
Peak_Pos_Mx             7.011000000     92.34967314         578            1
Peak_Neg_Mx             6.908000000    -137.7246470         578            1
Peak_Pos_My             6.873000000     77.01443274         578            4
Peak_Neg_My             6.907000000    -101.0378914         578            1
Peak_Pos_Mxy            6.974000000     89.22790928         575            2
Peak_Neg_Mxy            6.905000000    -35.78935626         576            2
Peak_Pos_Sx             6.815000000     2812.237758         576            1
Peak_Neg_Sx             6.914000000    -2766.651117         576            1
Peak_Pos_Sy            0.1350000000     1978.966467         576            2
Peak_Neg_Sy             6.914000000    -1898.473033         578            2
#
#
```

The maximum positive and negative middle in-plane shear (Sxy) stress occurs at Gauss point 2 of element 576. Values of 2.67MPa at time 7.224 seconds and -13.6MPa at time 6.798 seconds are observed.

- Close the Notepad application and graph windows.

Save the model

File
Save…

- Save the model.

This completes the example.