DEVELOPMENT AND CONTROL OF A NOVEL TEST RIG FOR PERFORMING MULTIPLE SUPPORT TESTING OF STRUCTURES

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ABSTRACT :

Multiple support excitation is caused when different ground inputs occur along the length of a bridge. Much research has been carried out on modeling long span bridges with multiple support excitation both numerically and analytically, however there have been few successful experimental models investigating the effect of this type of input motion on large scale bridges. This paper outlines the design and construction of a unique multiple support excitation experimental test bed. The bed comprises 5 single axis shaking tables which are independently controlled by 5 actuators. The shaking tables are steel boxes each mounted on a single 50mm diameter rod. A pair of bearings prevents each table rotating around the horizontal axis, perpendicular to the rail. To prevent rotation of the tables around the rails the actuators are hung below the tables and this keeps the tables stable and upright. To date no significant spurious motions of the tables have been observed. This paper discusses the design of the test rig in detail and also addresses the control issues associated with operating this type of experimental rig where the interaction between the test specimen and the test rig itself can have a detrimental effect on the results of the tests. The results of the testing of MSE on bridges have revealed that multiple support excitation can be a significant factor in the behavior of bridges with moderate spans of 200m.

KEYWORDS: Bridges, shaking table, physical test, control

1. INTRODUCTION

When designing long span bridges Eurocode 8 pt 2 requires that the designer considers the effects of spatially varying ground support motions. These spatially varying ground support motions are also known as multiple support excitation (MSE). The ground motion caused by an earthquake travels as waves. These waves have a finite velocity and therefore will arrive at support locations at different points in time. Furthermore as the waves reflect and refract they start overlapping causing interference. Different MSE effects include the time delay between inputs (the wave passage effect) and the differences in phase of different frequencies of the input motion (the soil effect), this second effect can lead to completely different input motions at each support. Much analytical research has been carried out both in the area of modelling the input motions (Der Kiureghian, 1996) and in the response of structures to these input motions (Hao, 1998; Lupoi et al. 2005). This work has shown that MSE may significantly increase the response of long span bridges but these findings have not been validated by any experimental tests.

2. PREVIOUS EXPERIMENTAL STUDIES

Prior to the work at the University of Bristol only one set of MSE experiments has been performed (Pinto et al, 1996). These experiments involved a large scale bridge model being shaken by 3 separate shaking tables. The stiffness of the bridge model led to a large degree of interaction between shaking tables and the control of the separate shaking tables was therefore limited. As a result the experiments were inconclusive.

Previous studies at the University of Bristol include prototype testing of a single bay portal frame single degree of freedom structure with two inputs (Wagg et al, 2002; Virden et al, 2004). This experimental set up can be seen in figure 1. Following this work the level of complexity of the system was increased by considering a two degree of freedom axial spring model, which approximates a portal frame or bridge structure with two dominant modes (Normal et al. 2004), the experimental set up can be seen in figure 2.


Figure 1. The single (inverted) portal frame MSE experimental set up.

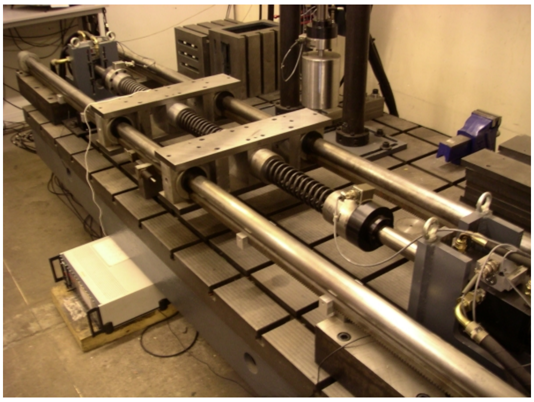
Figure 2. The two DOF axial spring MSE experimental test bed.

The new BLADE (Bristol Laboratories for Advanced Dynamic Engineering) project and specifically the EQUALS laboratory (EarthQUakes And Large Structures) provide cutting edge research facilities including a 6 axis shaking table, 20 m of head room, strong walls and floors and a suite of actuators with a hydraulic ring main running around the perimeter of the laboratory. The strong walls include a 1m thick concrete section which forms one end of the laboratory creating a box with one side open. The rest of the laboratory has 500mm thick strong walls. Experiments are attached to the strong walls and floor by means of T slots (made from prefabricated channel sections) cast into the walls and these allow attachment to the walls and floors using connecting plates clamped to the inside of the T slot flanges. These facilities have made it possible to create the first dedicated multiple support excitation test bed facility (figure 3).


Figure 3. The shaking table test bed with bridge model mounted on top.


Figure 4. Bridge model side view.

3. DESIGN OF THE BRIDGE PROTOTYPE

The bridge prototype is a 200m long bridge with three piers at equal spacing. The prototype dimensions were based on previous numerical MSE models which used a similar arrangement and showed that MSE can have a significant effect on the response of this size structure (Lupoi et al. 2005). These dimensions have also been used in other experimental work on bridges with synchronous inputs (Zapico et al. 2003) as well as in the previous MSE experimental study previously mentioned (Wagg et al. 2002). The model falls within the Eurocode 8 pt 2 size range for bridges of non-uniform soil type but does not fall within the size range for bridges with uniform soil types for which MSE should be considered. However a recent paper on the new Egnatia motorway in Greece (Ahmadi-Kashani, 2004) states that a substantial number of bridges, 103 of 612, are between 100 m and 300 m whilst only 14 are longer than 400 m, the minimum size for considering MSE for uniform soils in accordance with Eurocode 8 pt 2.

The experimental bridge is a 1:50 scale model of the bridge prototype. It is constructed from a single 60*60*3.2 SHS 4 m long (figure 4). The three piers occur at 1 m intervals and the end abutments are created using a steel pin, which passes through the tube, allowing the bridge deck to rotate in plan but not in elevation (figure 5). The piers are made from 20 mm by 25 mm solid steel bar which are welded to fixing plates at the bottom, forming an encastré base connection (figure 6). The top of the piers has a slot and key clamped connection which provides a fully fixed connection between the pier and the deck; however the connection is designed to be quickly interchangeable allowing different pier lengths to be inserted without having to remove the bridge from the experimental test bed (figure 7).

Figure 5. Abutment pin connection.

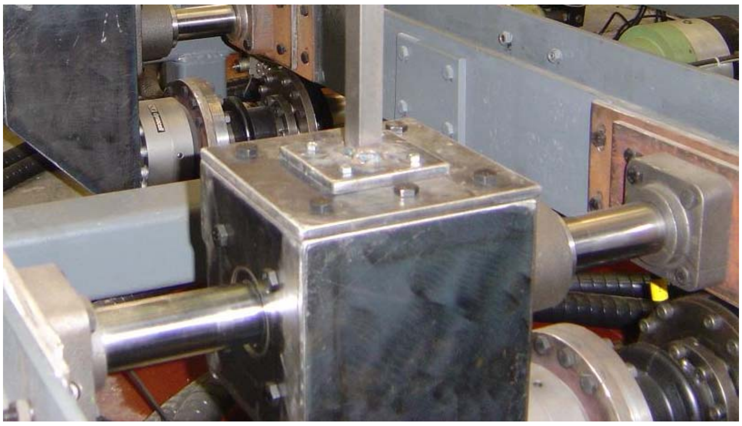

Figure 6. Pier connection detail to shaking table.

Figure 7. Pier connection detail to underside of bridge deck.

Three piers lengths have been investigated, 425 mm, 215 mm and 145 mm. These piers lengths are also based on previous numerical and experimental studies (Lupoi et al. 2005, Zapico et al. 2003). The various pier lengths lead to 18 possible combinations of bridge pier arrangement, representing different ground topography and therefore different responses of the bridge to excitation. The piers are orientated so that when the bridge is shaken they deflect in the direction of their weaker minor axis. This has been done for two reasons; firstly the piers will not buckle in bending when they are excited in their non-linear range; secondly, the stiffness of the piers in their major axis helps to prevent the shaking tables from rotating during shaking. In this paper only data for a symmetrical bridge with long piers (425 mm) at all three locations is considered. This bridge structure has many dynamic mode shapes, however we are interested, at this stage, in just the first three. This is because the first three modes dominate the response of the bridge structure and therefore can be easily measured in the laboratory, even for relatively small input displacements. The higher modes have a much smaller effect on the response of the bridge and are therefore much harder to measure. The first three modes can be seen in figure 8 and as can be seen the first and third modes are symmetrical, whilst the second mode is asymmetrical.

1st Mode, 27.8Hz, Lat 2nd Mode, 34.5Hz, Lat 3rd Mode, 39.8Hz, Lat

Figure 8. The first three mode shapes of the bridge.

The bridge deck itself has 160 masses attached to it in groups of four, 10 between each pier (figure 4). These additional masses significantly reduce the natural frequency of the structure so that the first 3 modes are at 5.4, 10.2 and 16.3 Hz, this relates to full scale natural frequencies of 0.76, 1.44 and 2.31 Hz respectively.

4. DESIGN OF THE TEST BED

The MSE test bed is specifically designed to simulate MSE. It comprises of 5 single axis shaking tables which are independently controlled by 5 actuators (figure 9).

Figure 9. The multiple support excitation test bed.

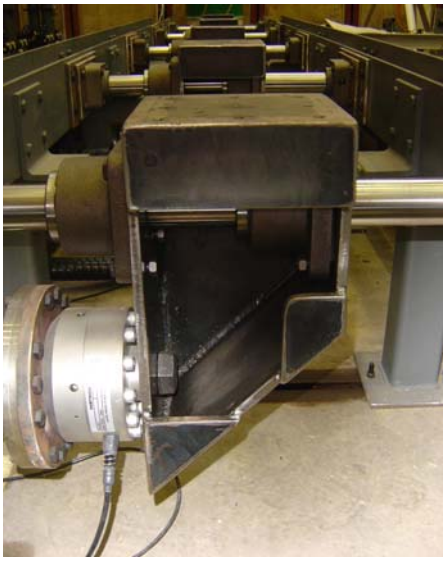

Figure 10. Shaking table side view

The shaking tables are steel boxes, with one side open to enable access to the bearing mounts and the fixing to the actuator (figure 10). The shaking tables are mounted on a single 50 mm diameter rail. The shaking tables run on two sets of bearings, one is fixed to the inside of the shaking table whilst the other is fixed to the outside (figure 11). The pair of bearings prevents the table rotating around the horizontal axis, perpendicular to the rail. This is required to prevent the shaking tables rotating during excitation as the actuators, which are fixed below the bearings, apply an eccentric load. These rotations are of particular significance when the structure is not attached directly to the shaking table but is instead attached to stiff extensions as these stiff extensions amplify displacement due to the rotations. A single rail was preferred to two rails so that lock-up of the system, which occurs when two or more rails are misaligned, did not occur. Unfortunately using just a single rail system does mean that the shaking table is not prevented from rotating around the axis of the rail. However, in this case, the design of the shaking tables means that the weights of the actuators keep the tables stable and upright. To date no significant spurious motions of the tables have been observed.

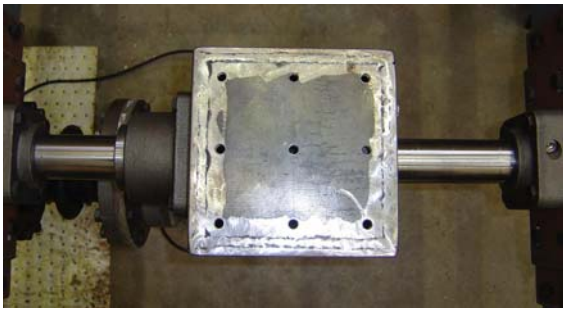
Figure 11. Shaking table top view.

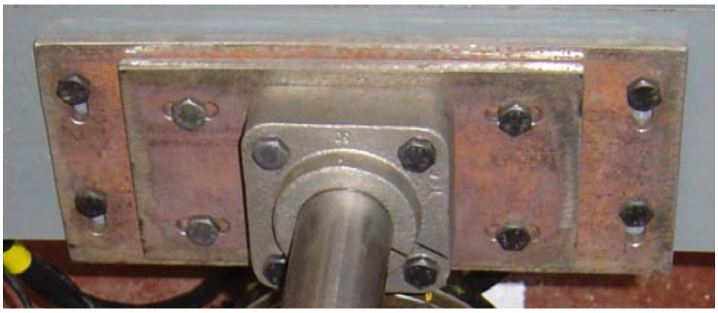
Figure 12. The shaking table rail fitting and adjustable plate.

Each end of the rails is attached to a system of two adjustable plates, with slotted holes, the first plate has holes orientated horizontally, the second vertically. These enable the rails to be lined and levelled to an accuracy of greater than +/- 1 mm (figure 12). The bolts then hold the plates in place and are regularly checked to ensure no slippage has occurred during the running of the test bed.

The test bed is held together by two 152 UCs which are aligned along their minor axis. This enables a simple connection between the adjustable plates and the UC, but more importantly was designed to withstand a lock up of any shaking table which could lead to a sudden impact load of up to 50kN being applied by the actuators. The maximum vertical load on the beams, by comparison, is only 1 kN.

The UCs are supported by 6 mini portal frames, constructed from 100*100*5 SHS. Each portal frame is bolted down to the strong floor by means of the T-slots. The frames are assumed to be pinned at the base, although the T-slot connection will provide a certain degree of fixity.

The actuators are attached to the shaking table via a force transducer. The force transducer is used in the control of the actuators and is also part of the safety system of the test bed. The test bed stops when the force transducer exceeds 10 kN, 20% of the actuators' capacity, which only occurs during lock up of the system, and hence the test bed is never required to resist the full load of the actuators.

The actuators themselves are high specification 50 kN actuators, previously used on the old University of Bristol shaking table. They have 2 Moog servo valves and can operate at frequencies from 0 Hz to 100 Hz. The actuators can produce accelerations in excess of 6 g and can move by +/- 150 mm, although the tables themselves may only move by +/- 100 mm. The actuators are attached via a hydraulic station with small accumulators to the hydraulic ring main which can provide up to 1200 l/min at a pressure of 210 bar, which is significantly more than is required to run the actuators at full capacity. The hydraulics are connected by means of quick release fittings, the return pipe having a larger bore to prevent the flow of oil being restricted. The quick release fittings are intentionally designed so that the wrong pipes cannot be plugged into the wrong fittings, by varying the sizes of the quick release.

The back of the actuators is connected to a 203 UC, this beam is larger than the beams supporting the shaking tables to enable the actuator pin connection adequate depth for connection. The UC is connected directly back onto the laboratory strong wall where possible. Where it is not possible the 500mm difference in wall thickness was made up by fixing 100*100*5 SHS props between the wall and the UC. The UC is supported by short 100*100*5 SHS which fix to the floor T-slots. As a result the actuators are held in position at this end so that the displacements during shaking are negligible.

5. DESIGN OF THE SHAKING TABLE EXTENSIONS

The varying pier lengths which relate to different topography of the ground spanned by the bridge required the base excitations for the piers to occur at different heights. To achieve this either the shaking tables needed to be placed at different levels or the shaking tables needed to be placed at the same level and the difference in height needed to be made up with a stiff element such that the excitation at the shaking table and at the top of the stiff element were the same.

To enable the piers to be easily interchangeable stiff table extension have been used. The extensions are made from 200*100*10 RHS and finite element modelling has shown that they only start interacting significantly with the structure at the 8th mode which occurs at approximately 73.9 Hz. At present we are only interested in the first three modes of the structure, and we are only controlling inputs with any certainty up to 40 Hz.

6. CONSTRUCTION OF THE TEST RIG

Whenever possible, at the University of Bristol, steelwork and other materials are recycled. In this case the 100*100 SHS was recycled, the rest of the steel work was designed and detailed in-house and was supplied by a fabricator. The steelwork was welded in-house except for the shaking tables which the fabricators made. The whole test bed and model is designed to be demountable and recyclable and as a result all connections are bolted except for the portal frames.

During the construction, operation and decommissioning health and safety is of the utmost concern. In particular, risk assessments have been written for all aspects of the build, maintenance, operation and decommission process.

7. INPUT EXCITATION

The inputs into the rig comprise of actual recorded earthquake time histories (Alexander et al. 2006) and artificially generated time histories which are response spectrum compatible in accordance with Eurocode 8 pt 1. The real earthquake time histories were taken from data recorded from the SMART1 array (Loh et al. 1982), an array of accelerograms designed specifically to measure differences in ground motions. Only the response spectrum compatible results are presented in this paper. The response spectrum compatible earthquakes were created using (Clough and Penzien 1993) and were fitted to a Eurocode 8 pt 1 response spectra for firm ground, response spectra type 1. The inputs were run through the test bed both synchronously and with a time delay of 7 ms between each input. This is equivalent to a surface wave velocity of 1000 m/s the velocity given by Eurocode 8 part 1 for firm ground.

The input motions for the test bed were defined in terms of displacement rather than accelerations for control reasons. To create these displacements the artificial acceleration records were double integrated with a Butterworth high pass filter applied at each stage to prevent drift of the input motions. The displacements were back differentiated and compared with the original accelerations and response spectra to check that the motions had not been degraded by the processing. The displacements were then normalized and their peak value was set to 1 mm. This prevented the piers from entering their plastic range during this initial set of tests which aimed to keep the materials in the linear range only. Using the FE model it was determined that 1 mm peak input displacement would lead to peak displacements of 6 mm at the tops of the piers, by comparison calculated showed that the piers would enter their plastic range at 8 mm.

8. TYPICAL RESULTS

Figures 13 and 14 show typical results from the test bed. The responses shown are the displacements at the top of each pier during the earthquake. The results clearly show that when the time delay is included there is a larger response in the first and third piers, whilst there is no reduction in response of the middle pier. This is because the synchronous input only excites the symmetrical first and third mode, whilst the time-delayed input excites the first three modes.

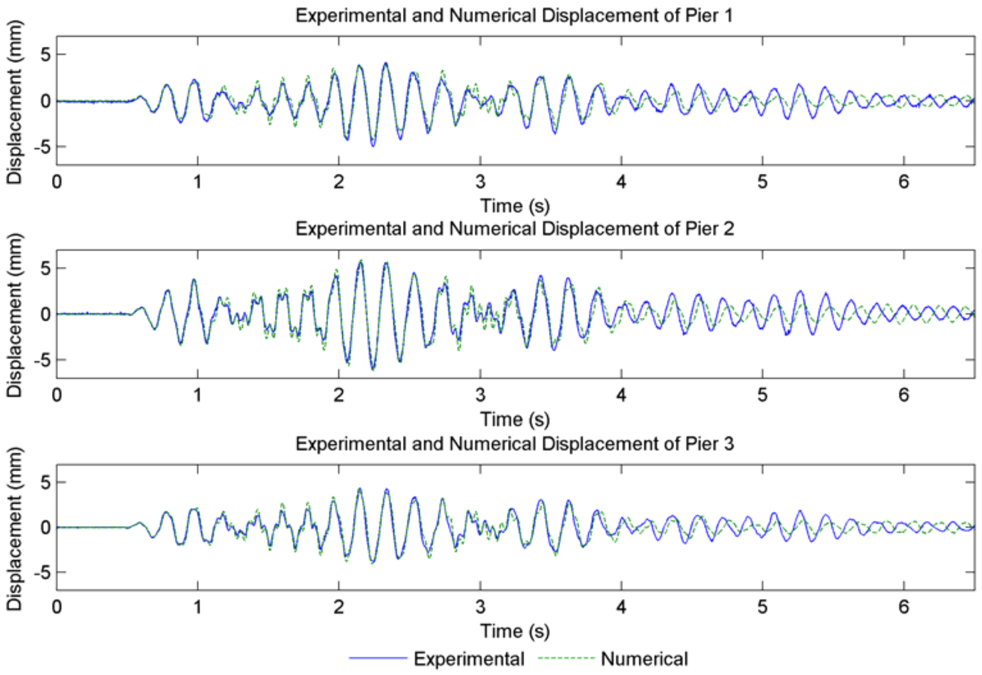

Figure 13. Displacement at the top of the three piers when subjected to synchronous time history.

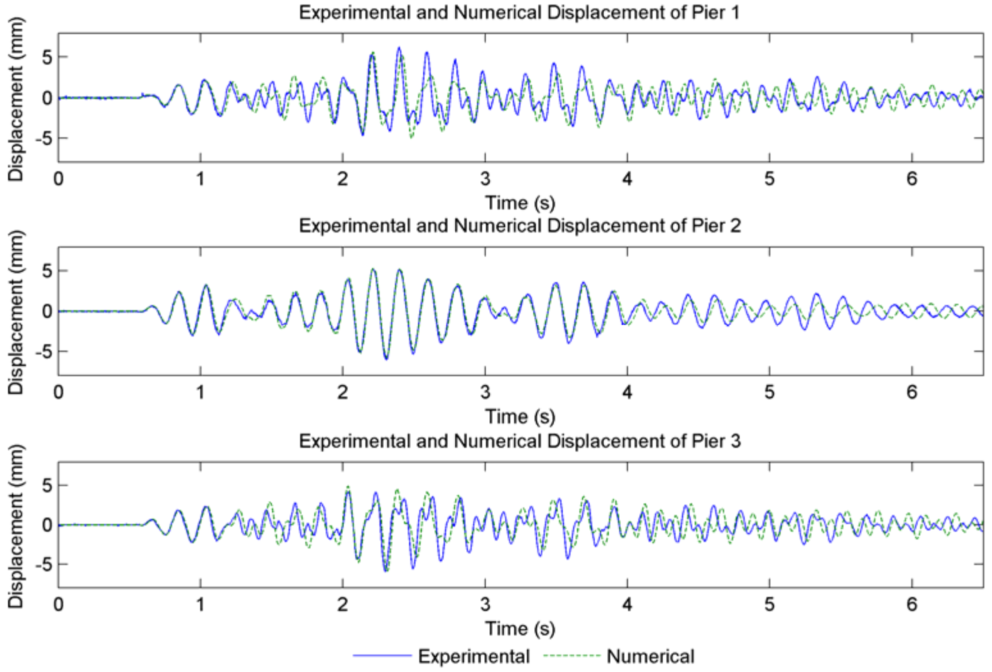

Figure 14. Displacement at the top of the three piers when subjected to time history with a 7ms time delay between each support.

These typical results reveal that if we consider synchronous excitations only, the response of some piers may be underestimated and hence the design may be unsafe. As noted earlier, at present the Eurocode 8 pt 2 does not requires bridges of this size to be analysed under MSE if the ground conditions are homogenous. However, this typical result reveals that even though the response spectra was identical for all inputs, with only a small time delay between inputs at each pier, the response of the outer piers was significantly increased.

9. CONCLUSIONS

In this paper we have presented the design and build of a multiple support excitation test bed and have presented experimental results for a typical case of multiple support excitation of a long span bridge. The inputs were response spectrum compatible artificially generated displacement time histories, with and without time delays. The results show that even for this moderate length bridge model multiple support excitation can increase the response of the bridge piers.

Future work on this topic will include using bridges with different geometries, looking at different input types including incoherent inputs and inputs with a loss of coherence. In addition we plan to consider the effect of varying soil conditions along the length of the bridge. Work will also be carried out on the bridge response when the piers enter their non-linear range. Finally, we are interested in the possibility of extending this work to hybrid testing, where the soil is modelled numerically whilst the bridge is modelled experimentally.

10. ACKNOWLEDGEMENTS

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