The effect of retrofitted shear connection systems on the dynamic response of composite concrete steel beams

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THE EFFECT OF RETROFITTED SHEAR CONNECTION SYSTEMS ON THE DYNAMIC RESPONSE OF COMPOSITE CONCRETE STEEL BEAMS

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ABSTRACT

Of the nearly 5000 bridges in New South Wales, about 17% are more than 50 years old. Most of these older bridges are considered structurally deficient by modern standards for the loads they are required to carry. These bridges will have to be replaced or strengthened by utilizing post installed shear connection systems. In this project two types of blind bolt connectors are being used as shear connection systems in steel-concrete composite beams alongside a welded shear stud system, and a non composite beam for comparison. The use of high strength non shrink grout in retrofitting procedures for shear connections can lead to differences in modal parameters of beam specimens to varying degrees at different levels of induced damage. This phenomenon has an effect on the way in which changes in modal parameters are interpreted in structural health monitoring systems. An experimental series is presented with two specimens for each type of shear connector. The first set is cast in whilst the second set is retrofitted. Each of the specimens is tested in intervals to destruction and the result compared.

KEYWORDS

Composites, retrofitting, vibration, dynamic response.

INTRODUCTION

Sustainability has become increasingly important in civil engineering. With finite resources and expensive construction costs repurposing construction materials or rejuvenating existing structures has become of great interest. Retrofitting structures with shear connection systems to achieve composite action could be a cheaper alternative to replacement of the entire structure. Much research has been conducted on the invention of post installed or retrofitted shear connectors (Lam and El-Lobody 2005; Qureshi et al. 2010; Kwon et al. 2011; Lam and Saveri 2012; Pavlovic et al. 2013). Most of the current research revolves around modified versions of welded shear studs or various threaded rod and nut configurations. It is evident that for the advancement of research in retrofitting and demounting structures, new innovative anchors must be found which are suitable for the purpose. Recently, the authors have developed works based on shear connection systems using innovative anchors, (Mirza et al. 2011a; Law and Zhu 2009; Mirza et al. 2011b). The concrete-steel composite action is achieved with the use of ‘blind bolts’ to connect structural steel beams to concrete slabs. The blind bolts under consideration can be undone once fitted this makes them suitable for use in both new construction and for where existing steel infrastructure is being rehabilitated. The use of blind bolts in new construction will enable buildings involving multiple dissimilar materials to be connected and will also facilitate the deconstruction of steel structures. The use of blind bolts will also mean easier remediation where
steel members may be in jeopardy of fatigue failure in existing infrastructure. Assessing the condition of the shear connectors once they are in place and being able to detect the integrity of the existing shear connectors before retrofitting/strengthening existing structures then becomes of paramount importance. The inaccessibility of the connection system makes direct inspection difficult. Also, the huge number of shear connectors prevents any local non-destructive testing methods to access the connectors one by one, (Mirza et al. 2011a; Law and Zhu 2009). Vibration based methods have been widely used in the analysis of civil engineering structures, (Carden and Fanning 2004; Doebling et al. 1998) and may be suitable for this purpose. An experimental study has been undertaken to ascertain the dynamic behaviour of identical steel-concrete composite beams with differing shear connection systems. Two blind bolt connector types were used as shear connection systems in the steel-concrete composite beams. Alongside these, a welded shear stud system, and a non-composite beam were tested for comparison along with a complementary set of push tests. The experimental results for the six steel-concrete composite beams and twelve accompanying push tests are presented along with observations and a dynamic analysis. Dynamic responses to impact hammer excitation were recorded using an NI PXIe data acquisition system and modal parameters were extracted using DIAMOND, a MATLAB based program.

CONNECTOR TYPES

Figures 1(a) to (d) show the three shear connector types considered in this experimental series. Figure 1(a) is hereafter known as the B1 type connector. Figures 1 (b), and (c), show the B2 type connector in both the open and closed configuration. Figure 1(d) shows the SS shear connector which is a simple welded stud. For differentiating between cast in or retrofitted connectors an r or a c in brackets is placed after the connector type. For example SS(c) for a cast in shear stud.

![Connector types: (a) B1, (b) B2 closed, (c) B2 open, (d) SS](image)

RETROFITTING PROCEDURE

The retrofitting procedure involved drilling through the concrete from the top side of the slab. The steel section then had holes drilled into it through the hole in the concrete section. This was done as part of the overall ethos of the project is the possibility of retrofitting bridge structures where access may be restricted to the deck side. The holes for different shear connector types are different sizes. The SS, B1, and B2, slab hole diameters were 100mm, 70mm, and 50mm respectively. Once the shear connectors are fitted the holes in the concrete are back filled with a high strength non shrink grout.

![Retrofitted cross section](image)

The hole diameters were chosen as the smallest possible for each respective shear connector type. The B1 connector only required a socket to be fitted down the hole. The B2 connector requires more space as when it is secured the collar needs room to spread. The SS type connector required the largest hole as room for welding equipment needs to be provided.
EXPERIMENTAL SERIES

A series of composite steel-concrete beams were designed with a partial shear connection of seventy to eighty percent. Three of the specimens had the SS, B1, and B2, shear connectors installed prior to the concrete pour, i.e. cast in. A further four specimens were cast as non composite sections. Three of these beams were retrofitted with the SS, B1, and B2, shear connectors. The final non composite specimen was used as a comparison but is omitted from this paper for brevity. Two push tests were also conducted per connector type and fitting procedure giving a total of twelve push tests in total, six cast in and six retrofitted.

Push Tests

The push test layout for this study is shown in Figure 3. From the side view it is apparent that the stud layout is different from the standard in (Eurocode 4 2005). The push test has an asymmetrical distribution pattern and the number of studs used is half that of a normal push test specimen. This was done to mirror the staggered layout and spacing used in the full sized test specimen. In (Eurocode 4 2005) there is a clause which allows for variation of the shear connector layout. In such cases the load carrying capacity (\(P_{Rk}\)) is taken as ninety percent of the minimum failure load across four push tests (Eurocode 4 2005).

Push Test Results

The results of the push tests are used to determine the value of the shear connector stiffness (\(k\)). The load was applied up to 40% of their design capacity and then cycled between 5% and 40% 20 times before loading until failure at a rate of 1.4mm per minute. Figures 4 (a), (b), and (c) show the load-displacement curves for the push test results of the three different shear connectors both cast in (c) and retrofitted (r). In Figure 4 (b) the B1-1 (c) specimen shows some initial slip when the load first reaches 80kN this is not a defective specimen but rather it is a characteristic of the shear connection type used. The B1 type connector has a stepped washer either side of bolt passing through the flange of the steel section. This creates potential for movement as the initial load is applied.

The slope of each repeated loading cycle was isolated and fitted with a linear trend line. The mean and standard deviation of these were then calculated across both specimens for each connector and
installation type. Table 1 shows the mean shear connector stiffness for each push test type. The standard deviations between samples ranged from 8 to 15 kN/mm across all the specimens. Therefore the stiffness of the connectors is comparable between the cast in and retrofitted push tests specimens even though the ultimate loads and failure conditions may vary.

<table>
<thead>
<tr>
<th>Connector</th>
<th>SS (c)</th>
<th>SS (r)</th>
<th>B1 (c)</th>
<th>B1 (r)</th>
<th>B2 (c)</th>
<th>B2 (r)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean k (kN/mm)</td>
<td>156.47</td>
<td>157.16</td>
<td>163.89</td>
<td>166.81</td>
<td>180.94</td>
<td>173.28</td>
</tr>
</tbody>
</table>

Experimental Setup for Full-Scale Beam Testing

Figure 5 shows the top view of the beam specimen. The concrete section dimension is shown as 6200mm x 1000mm and the depth of the concrete section is 150mm. Allowing for the end spacing of 110mm and intermediate spacing of 230mm gives a total of 27 shear connectors on each specimen. The steel beams were universal beam sections of 460UB 74.6 with a length minimally longer than the concrete section at 6220mm. The inset of the shear connectors from the edge of the flange was 47.5 mm. Each specimen was simply supported with a 6m span. There were two loading points, shown by the shaded areas. The central axes of the loading points are 1m apart and equidistant from the central axis of the beam. The loading points are 100mm wide and cover the full 1000mm width of the beam.

A total of thirty six accelerometers divided into four sets were utilized. Three rows of nine accelerometers were placed on top of the concrete section and one row of nine accelerometers was placed on the steel section all at equal 750mm spacing. The hammer location was 200mm inset from the edge and 1800mm from centre of the beam. This location was chosen to not be too close to any individual accelerometer and also to not be on a node of the first few modes of vibration. The numbering convention and hammer location can be seen in Figure 6.

Test Procedure

A 1000kN hydraulic jack was used for the four point loading system. Different damage scenarios were created with 20%, 40%, 60% and 80% of the calculated ultimate capacity. After each loading target was achieved the load was removed and dynamic testing undertaken. Including the initial and failure stages this gave a total of six dynamic testing stages for each beam specimen as shown in Table 2. The numbering system for accelerometer locations can be seen in Figure 6. The dynamic measurements were taken for all locations simultaneously and repeated six times. The results of the six repetitions
were averaged together in the frequency domain to reduce noise. A rational polynomial method was then used in conjunction with the imaginary part of the frequency response function (FRF) to gain the frequencies, damping, and mode shapes of the specimen.

**Observations**

A note worthy general observation was made on the failure modes of the cast in versus the retrofitted beam specimens. The retrofitted beams exhibited all the general failures of the cast in series such as failure of shear connectors and major cracking under the loading points as shown in Figure 7 (a). However, the retrofitted beams also exhibited failures in the form of longitudinal cracking down the centre of concrete section running between and around the high strength grout as shown in Figure 7 (b).

![Figure 7. (a) Failure at the loading point, (b) Failure at the high strength grout](image)

**Results**

Table 2 shows the frequency results of all six shear connected specimens. The damping ratios have been omitted for brevity. Modes B₁ to B₆ refer to bending modes 1 to 6 and the load stages 0 to 5 refer to the percentage loading states with 0 being prior to loading and 5 being 100%. The c and r in brackets refer to cast-in and retrofitted specimens respectively.

<table>
<thead>
<tr>
<th>type/mode</th>
<th>0(c)</th>
<th>0(r)</th>
<th>1(c)</th>
<th>1(r)</th>
<th>2(c)</th>
<th>2(r)</th>
<th>3(c)</th>
<th>3(r)</th>
<th>4(c)</th>
<th>4(r)</th>
<th>5(c)</th>
<th>5(r)</th>
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<td>SS-B₁</td>
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<td>25.3</td>
<td>24.6</td>
<td>24.8</td>
<td>24.5</td>
<td>24.2</td>
<td>24.5</td>
<td>23.6</td>
<td>24.4</td>
<td>22.9</td>
<td>22.6</td>
<td>22.2</td>
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<td>96.2</td>
<td>95.8</td>
<td>93.8</td>
<td>96.6</td>
<td>90.4</td>
<td>96.0</td>
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<td>220</td>
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<td>288</td>
<td>381</td>
<td>272</td>
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<td>259</td>
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<tr>
<td>B₁-B₁</td>
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<td>24.9</td>
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<td>21.8</td>
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<td>21.8</td>
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<td>B₁-B₂</td>
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<td>B₁-B₄</td>
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<td>B₂-B₁</td>
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<td>22.7</td>
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<td>22.6</td>
<td>21.6</td>
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<tr>
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<td>291</td>
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<td>284</td>
<td>258</td>
<td>271</td>
</tr>
</tbody>
</table>

Table 2. Frequency results for cast in and retrofitted specimens
Comparing the cast in and retrofitted specimens change in frequency of modes $B_1$ to $B_6$ with increased loading some important behaviours can be seen. The SS connector with the largest diameter hole has the closest match in frequency prior to loading but also decreases the fastest as the load increases. The spread of the frequency response between loading stages of the $B_1$ and $B_2$ type connectors with the smaller diameter holes are much more consistent. However, the overall frequency response was much lower compared to the cast in equivalent.

CONCLUSIONS

The results show that there was a marked difference in dynamic behaviour between the cast in and retrofitted shear connection systems. Also, the difference in behaviour was not consistent across the three shear connection types. There are two factors possibly responsible for this. Firstly the interface between the high strength grout and the concrete created a discontinuity as shown in Figure 7 (b). This had a different surface area depending on the diameter of the hole and therefore could have been an important dissimilar parameter between specimens. Secondly, with the high strength grout being de-bonded from the concrete, the holes acted as stress concentrators. The smaller holes then developed longitudinal cracks down the centre of the concrete slab between the holes at an earlier loading stage than the larger diameter holes.

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