BEHAVIOUR OF THE HEADED STUD SHEAR CONNECTORS ON
Composite Steel-Concrete Beams under Elevated Temperatures Utilising Carbon Nanotube

Olivia Mirza [a], Kathryn Wilkins [a]

[a] University of Western Sydney, School of Computing Engineering and Mathematics, Locked Bag 1797, Penrith, 2751, New South Wales, Australia

Abstract

This paper describes the ultimate loads and failure modes of composite steel-concrete specimens when carbon nanotube is implemented. This paper also compares the load versus slip relationship of push tests under ambient temperature, at-fire exposure and post-fire exposure. Results from the experimental study demonstrated that the reduction of ultimate load and stiffness as temperatures increased. The at-fire exposure specimens showed a decrease in ductility as temperatures increased. Whilst, the post-fire exposure specimens showed an increase in ductility as temperatures increased. Even though carbon nanotube did not show increment in ultimate load, however the carbon nanotube reduced concrete spalling and cracking when compared to normal concrete under elevated temperatures.

Keywords: composite steel-concrete, push tests, shear connectors and elevated temperatures

INTRODUCTION

Composite steel-concrete beams consist of a concrete slab connected to a steel beam via headed stud shear connectors located at the interface of the components. Composite steel-concrete beams are considered effective due to the high concrete compressive strength complementing the high tensile strength of the steel component (Uy & Liew 2003). The headed stud shear connectors are used to prevent the vertical separation of the components, and also to transfer the normal and shear loads between the components (Lam & El-Lobody 2005).

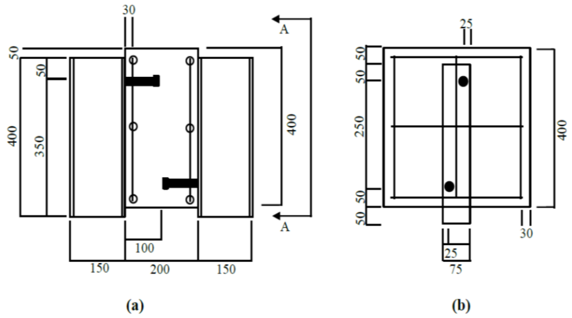
The integrity of fire-exposed structures is of high importance to understand. When exposed to elevated temperatures, the concrete and steel mechanical properties decrease with increasing temperature (Mirza and Uy 2009). As the headed stud shear connectors are indirectly exposed to the elevated temperatures, axial tensions are experienced from the imposed vertical uplift forces (Wang 2005). Research regarding the integrity of post-fire exposed structures is limited.

Carbon nanotubes are considered a smart material with research suggesting effective properties to be gained. When added to concrete mixture, the carbon nanotubes are expected to increase the compressive strength of the concrete component, and overcome concrete durability issues (Potapov et al. 2011). However, the experimental research regarding carbon nanotube concrete at elevated temperatures on composite steel-concrete structures has not been explored. This paper is to look at the effect of carbon nanotube on headed stud shear connectors for composite steel-concrete beam under elevated temperatures.

1 EXPERIMENTAL STUDIES

The push test method was conducted according to Eurocode 4 (British Standards Institution EC4 2005). The push test method involved applying a shear load directly to the headed stud shear connectors. The push test specimens were formed by a reinforced concrete slab standing vertically with two structural steel beams connected via the flanges by welded headed stud shear connectors. Two types of push tests were conducted, including normal concrete material and carbon nanotube concrete material.

For this experimental study, 400mm long 150UB14.0 Grade 300MPa structural steel beams were used. The reinforced concrete slabs had dimensions of 400mm wide, 400mm long and 200mm deep. The concrete used was 25MPa concrete. The nanotube concrete mixture had an addition of 1% carbon nanotube to concrete material. Three N12 reinforcing bars were spaced at 170mm centre to centre in the concrete slab. 19mm diameters with 100mm long headed stud shear connectors were used. The push test specimen setup for the normal concrete and carbon nanotube concrete materials are shown in Fig. 1.



(a) (b)

Fig. 1 Push test specimens

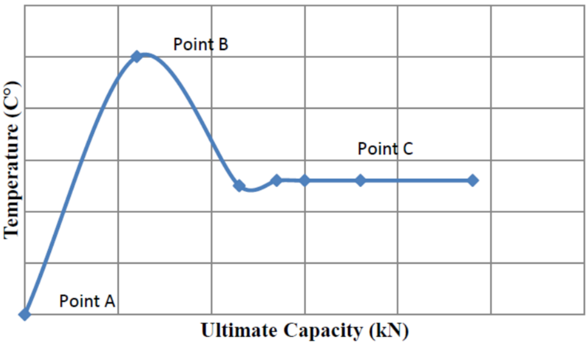


Fig. 2 Push test specimens under different conditions

Eurocode 4 (British Standards Institution EC4 2005) requires push test specimens using concrete to be of 600mm wide, 600mm long and 150mm deep dimensions. However due to the size limitation of the furnace, modifications to the push test specimens have been made. Hence the concrete component is 400mm wide, 400mm long and 200mm deep.

A total of 28 push test specimens were tested: 14 normal concrete and 14 carbon nanotube concrete materials. The three temperature conditions to be considered include Point A – ambient temperature, Point B – at-fire and Point C – post-fire exposure. The specimens were tested under ambient temperature, 200°C, post 200°C, 400°C, post 400°C, 600°C and post 600°C. Fig. 2 shows the push test experiment details and temperature conditions.

2 RESULTS AND DISCUSSIONS

2.1 Comparison of Push Tests Results for Normal Concrete at Fire

Generally, the specimens at ambient temperatures, 200°C and 400°C failed due to headed stud shear failure. The failure was signified by a large bang as the stud sheared off the steel flange, separating the concrete slab and steel beam components. For specimens at 600°C, the failure mode was caused by the combination of headed stud failure, concrete cracking and spalling failure. At the same time, it was also observed that the structural steel beam buckled due to the elevated temperatures.

Fig. 3 illustrates the comparison of push tests for the normal concrete at-fire exposure. Comparing the stiffness of the normal concrete at ambient temperature to 200°C, 400°C and 600°C, a reduction of 4%, 6% and 38% were observed, respectively. Overall, the ambient push test had the greatest stiffness. According to Mirza and Uy (2009) this is to be expected, as the increase in temperature steadily reduces the stiffness of the steel components. This is also due to the bond failure between concrete and steel surface when subjected to elevated temperatures.

The normal concrete ambient temperature push test achieved an ultimate load of 253kN. The 200°C, 400°C and 600°C normal concrete push test achieved an ultimate load of 223kN, 156kN and 89kN, respectively. This large reduction illustrates the increased danger of failure of composite steel-concrete beams when subjected to elevated temperatures. Overall the normal concrete ambient temperature specimen achieved the greatest ultimate load. This is due to the increased temperatures decreasing the mechanical properties of the composite steel-concrete specimens; specifically the compressive strength of the concrete component and the rigidity of the steel beam.

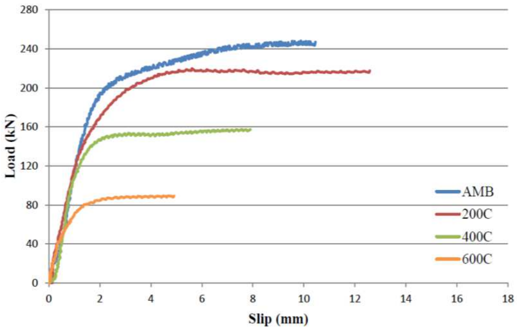


Fig. 3 Load versus slip relationships for normal concrete at-fire exposure

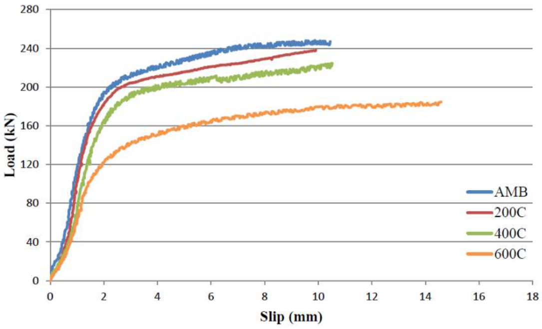


Fig. 4 Load versus slip relationships for normal concrete for post fire exposure

The normal concrete 200°C push test achieved the greatest ductility followed by the ambient temperature, 400°C and 600°C. Overall the ductility of the at-fire exposure specimens decreased as the temperature increased. This trend illustrates how the tensile strength of the headed stud shear connectors decreases as the temperature increases. The decreasing ductility of the specimens means the integrity of the structure reduces, as shorter failure periods occur.

2.2 Comparison of Push Tests Results for Normal Concrete at Post Fire

Similar failure modes were observed for normal concrete at post fire. The specimens at ambient temperatures, post-200°C and post-400°C failed due to headed stud shear failure. The failure was signified by a large bang as the stud sheared off the steel flange, separating the concrete slab and steel beam components. For specimens at post-600°C, the failure mode was caused by the combination of headed stud failure, concrete cracking and spalling failure. However buckling of the steel beam did not occur for the post-600°C specimen. This is because the specimen was not loaded whilst exposed to the elevated temperatures.

Fig. 4 demonstrates the comparison of push tests for the normal concrete at post fire exposure. The stiffness reduction of 11%, 39% and 45% between the normal concrete ambient temperature and post-200°C, post-400°C and post-600°C was observed. When compared to the normal concrete ambient temperature to at-fire push tests, similar trends of stiffness were observed. However, the normal concrete ambient temperature to at- fire push tests achieved a greater stiffness overall when compared to the ambient temperature to post-fire push tests. This suggests that the stiffness of the specimens continues to decrease and is not regained, once exposed to elevated temperatures.

An ultimate load of 253kN was achieved by the normal concrete ambient. The post-200°C, post-400°C and post-600°C normal concrete achieved an ultimate load of 237kN, 227kN and 183kN, respectively. This demonstrates an ultimate load reduction of 6%, 10% and 28% compared to the ambient temperature. In comparison to the normal concrete ambient temperature to at-fire push tests, the ambient temperature to post-fire push tests reduced in ultimate load at a significantly lower rate. This suggests that the ultimate load of the composite steel-concrete beams after exposure to elevated temperatures is greater than exposure during elevated temperatures. According to Fike and Kodur (2011), this is to be expected as the decreasing temperatures allow for the ultimate strength of the concrete and steel components to be regained.

The greatest ductility was achieved by the post-600°C push test. The ambient temperature and post-400°C push tests achieved similar ductility whilst the post-200°C push test achieved the lowest ductility. Overall the ductility of the normal concrete post-fire push tests increased as the temperature increased. This trend illustrates how the tensile strength of the headed stud shear connectors increases as the temperature increases. This trend is opposite to the at-fire exposure specimens. This suggests that greater tensile strength is regained as the specimens cool to ambient temperature. The increasing ductility of the specimens suggests the integrity of the structure also increases. This allows for longer periods of failure to occur, thus increasing safety.

2.3 Comparison of Push Tests Results for Carbon Nanotube Concrete at Fire

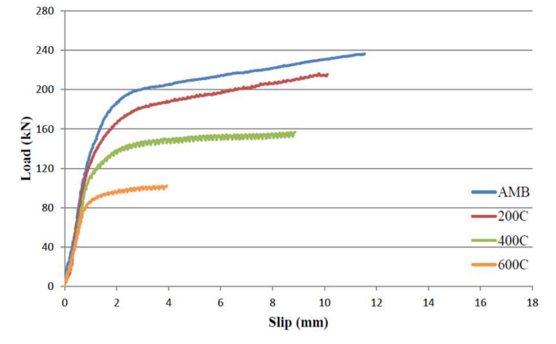
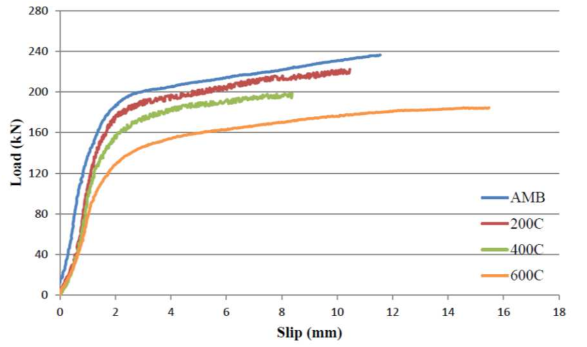
	

Fig. 5 Load versus slip relationships for carbon nanotube concrete at-fire exposure	Fig. 6 Load versus slip relationships for carbon nanotube concrete for post fire exposure

The failure modes for carbon nanotube are similar to normal concrete. This is due to the carbon nanotube not taking affect in increasing the compressive strength of the concrete. However, it was observed that the reduction of concrete cracking and spalling was observed when compared to the normal concrete at elevated temperatures. This is due to the nanotube concrete being able to prevent nano-cracks from occurring, by requiring a greater amount of energy to form the cracks (Konsta-Gdoutos et al. 2010).

Fig. 5 demonstrates the comparison of push tests for the carbon nanotube concrete at fire exposure. When compared with ambient temperatures, the stiffness of the nanotube concrete at 200°C, 400°C and 600°C illustrated an 8%, 18% and 38% reduction, respectively. When compared to the normal concrete ambient temperature to at-fire exposure push tests, similar trends of stiffness are observed. However the 200°C and 400°C normal concrete push tests achieved greater stiffness when compared to the nanotube 200°C and 400°C.

The nanotube concrete ambient temperature, 200°C, 400°C and 600°C achieved an ultimate load of 244kN, 204kN, 153kN and 100kN, respectively. When compared to ambient temperature, the ultimate load reduced 16%, 37% and 59%, respectively. In comparison to the normal concrete ambient temperature to at-fire push tests, the nanotube ambient temperature to at-fire push tests showed a similar trend in ultimate load reduction. More specifically, the nanotube at-fire push tests achieved a slightly lower ultimate load from ambient temperature to 400°C. However, from 400°C to 600°C, the nanotube at-fire push tests achieved a slightly higher ultimate load.

Overall the ductility of the at-fire exposure specimens decreased as the temperature increased. This trend in ductility is similar to the ductility trend of the normal concrete ambient temperature to at-fire push tests. The decreasing tensile strength of the headed stud shear connectors means the integrity of the specimen also decreases.

2.4 Comparison of Push Tests Results for Carbon Nanotube Concrete at Post Fire

The specimens at ambient temperatures, post-200°C, post-400°C and post-600°C failed due to headed stud shear failure. The failure was signified by a large bang as the stud sheared off the steel flange, separating the concrete slab and steel beam components. One improvement to these specimens, there were no sign of concrete cracking or spalling failure. This is due to the calciumsilicate hydro-crystals decomposing, allowing for the chemically bound water to be released and evaporated.

Fig. 6 demonstrates the comparison of push tests for the carbon nanotube concrete at post fire exposure. A 22%, 30% and 63% stiffness reduction was observed between the nanotube concrete ambient temperature and post-200°C, post-400°C and post-600°C, respectively. When compared to the normal concrete under ambient temperature and post-fire, the carbon nanotube ambient temperature and post-fire push tests achieved similar trends of stiffness. However, the normal concrete post-fire push tests achieved a greater stiffness. Greater stiffness was also achieved by the nanotube ambient temperature to at-fire exposure push tests when compared to the nanotube ambient temperature to post-fire push tests.

An ultimate load of 244kN was achieved by the nanotube concrete ambient temperature specimens. The post-200°C, post-400°C and post-600°C nanotube concrete demonstrated an ultimate load of 233kN, 197kN and 183kN, respectively. This illustrates an ultimate load reduction of 5%, 19% and 25% when comparing the ambient temperature push test to the post-200°C, post-400°C and post-600°C, respectively. Compare to the nanotube concrete ambient temperature to at-fire push tests, the ambient temperature to post-fire push tests reduced in ultimate load at a significantly lower rate. This is similar to the ultimate load trend between the normal concrete at-fire and post-fire push tests.

The greatest ductility was achieved by the post-600°C push test followed by the ambient temperature, the post-200°C and the post-400°C. This trend is opposite to the nanotube concrete ambient temperature to at-fire push tests, as the at-fire 600°C push test achieved the lowest ductility. Similarly, both the normal concrete and nanotube post-600°C push tests achieved the highest ductility when compared to the lower temperatures.

3 SUMMARY

The experimental studies showed that the failure modes for push tests were generally headed stud shear failure. Even though adding carbon nanotube into the concrete did not increase the compressive strength of the concrete, however, when the specimens were exposed to elevated temperatures, the reduction in concrete cracking and spalling were observed.

When comparing the normal concrete to the carbon nanotube concrete, it was observed that similar ultimate capacities were achieved. Similar rates in the reduction of the ultimate capacities were also achieved. Even though the carbon nanotube concrete had similar ultimate capacity as the normal concrete, the carbon nanotube concrete showed that there was a great reduction in spalling and cracking when exposed to elevated temperatures.

Furthermore, it can be concluded that the carbon nanotube material did not have any effect until temperatures reached 400°C or above. This is observed by the change in colour from the carbon nanotube concrete ambient temperature specimen to the 600°C specimen. This suggests that at greater elevated temperatures, the carbon nanotube concrete material would be a more effective choice, particularly with the reduced concrete spalling and cracking achieved.

In comparison of the at-fire exposure results to the post-fire exposure results, it was observed that greater ultimate loads and ductility were achieved by the post-fire exposed specimens, with similar stiffness achieved. This suggests that the strength of the components regains during the cooling process of the post-fire testing.

ACKNOWLEDGMENT

The authors would like to acknowledge the funding and financial assistance provided by Institute for infrastructures Engineering, University of Western Sydney. The authors also would like to acknowledge the technical staff at the University laboratory at the University of Western Sydney for their assistance, effort, hard work and overall dedication to the preparation of the experimental study push test specimens and to the conducting of the push test study. Lastly, the authors would like to acknowledge the School of Computing

Engineering and Mathematics at the University of Western Sydney for providing an exceptional learning environment, research facilities and materials.

REFERENCES

British Standards Institution EC4 2005, Eurocode 4 1994-1-1:2005, London.

Fike, R & Kodur, V, Enhancing the Fire Resistance of Composite Floor Assemblies Through the use of Steel Fiber Reinforced Concrete, Engineering Structures, vol. 33, pp. 2870-2878, 2011.

Konsta-Gdoutos, MS, Metexa, ZS & Shah, SP 2010, 'Multi-scale mechanical and fracture characteristics and early-age strain capacity of high performance carbon nanotube/cement nanocomposites', *Cement & Concrete Composites*, vol. 32, pp. 110-5.

Lam, D & El-Lobody, E, Behaviour of Headed Stud Shear Connectors in Composite Beam, Journal of Structural Engineering, pp. 96-107, 2005.

Mirza, O & Uy, B, Behaviour of headed stud shear connectors for composite steel-concrete beams at elevated temperatures, Journal of Constructional Steel Research, vol. 65, no. 3, pp. 662-74, 2009.

Potapov, VV, Shitikov, ES, Trutnev, NS, Gorbach, VA & Portnyagin, NN, Influence of Silica Nanoparticles on the Strength Characteristics of Cement Samples, Glass Physics and Chemistry, vol. 37, no. 1, pp. 98-105, 2011.

Uy, B & Liew, RJY, The Civil Engineering Handbook, eds WF Chen & RJY Liew, CRC Press, Chapter 51, via CRC netbase http://www.crcnetbase.com.ezproxy.uws.edu.au, 2003

Wang, YC, Performance of Steel–Concrete Composite Structures in Fire, Progress in Structural Engineering and Materials, vol. 7, no. 2, pp. 86-102, 2005.