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Lateral impact response of end-plate beam-column connections

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ABSTRACT

The behaviour of different steel beam to column connections has been studied intensively against static and seismic loading regimes. However, there is a lack of knowledge on the response of such connections against impact and blast. In order to close this gap, the most common connections with partially depth end plate (PDEPCs), as a simple connection, and flush plate (FPCs), as a moment resisting connection, were investigated under both quasi-static and impact loads. Here, eight specimens were tested under those loading conditions with different locations. 3 D finite element models were then developed and validated against the corresponding experimental results. Full range analyses of the connection responses under both loading regimes are then carried out using the validated FE models to examine the internal forces of the connections. Finally, the results of full analyses under both loading regimes were compared and dynamic increase factors (DIF) were proposed to assist predicting the impact response of these types of connections using the static analysis. The results showed that failure modes under both loading regimes were similar, but with the larger fracture on the PDEPC under quasi-static load than that under lateral impact. The DIFs were found to be between 1.02 and 1.21, 1.03 and 1.36 and 1.22 and 1.45 based on the bolt tensile strength, axial resistance and bending resistance of the connections, respectively. However, if based on the energy approach, the range of DIFs was recorded between 1.25 and 1.38 using the experimental results and between 1.19 and 1.34 using the finite element analysis results.

1. Introduction

In the past four decades, the structural engineers have given considerable attention on investigating the response of structural members subjected to accidental loads such as impact and blast. These loads may be resulted from faulty practice, terrorist attack or vehicle impact, etc. The collapse of Ronan point in 1968 alerted the structural designers to the problem of progressive collapse at which local failure of primary structural elements led to the collapse of the connected members [1] which resulted in a disproportionate collapse. SCI publication P391 [2] that presents the structural robustness of steel framed buildings in accordance with the Eurocode and UK National Annexes states that " In essence, the objective is to ensure that buildings do not suffer disproportionate collapse under accidental loading. Largely, this is assured in steel framed buildings by designing connections appropriately". Also, after the WTC collapse, it was reported that the connection response against impact and fire needs to be understood and quantified as critical components of structural frame [3]. Hence, it will be beneficial to investigate the dynamic behaviour of this critical part on the structural frame particularly for connections with a low moment resistance. In steel framed structures having simple or semi-rigid beam-to-column connections, the connections are likely to be weaker than the columns and beams. However, in this case, any local failure developed in the connection due to the accidental loading may likely be followed by a partially or entirely progressive collapse of the steel frame. Hence, connection response should be investigated prior to other steel frame components to prevent or reduce the possibility of progressive collapse occurrence.

Generally the impact loading could be transferred to any structural beam-to-column connection by either striking the beam or the column connected. However, columns are more likely to expose to such forces than beams such as vehicle impact, flying debris or internal explosion, as shown in Fig. 1. Consequently, intensive studies were carried out to investigate the response of different types of columns under such loads (Yu and Jones [4], Mannan et al. [5], Bambach et al. [6], Zeinoddini et al. [7,8], Al-Thairy [9], and Shakir et al. [10]). In those studies, axially and non-axially loaded columns were investigated experimentally and numerically under lateral impact loads. Nevertheless, the structural aspects of steel frames require columns to be connected

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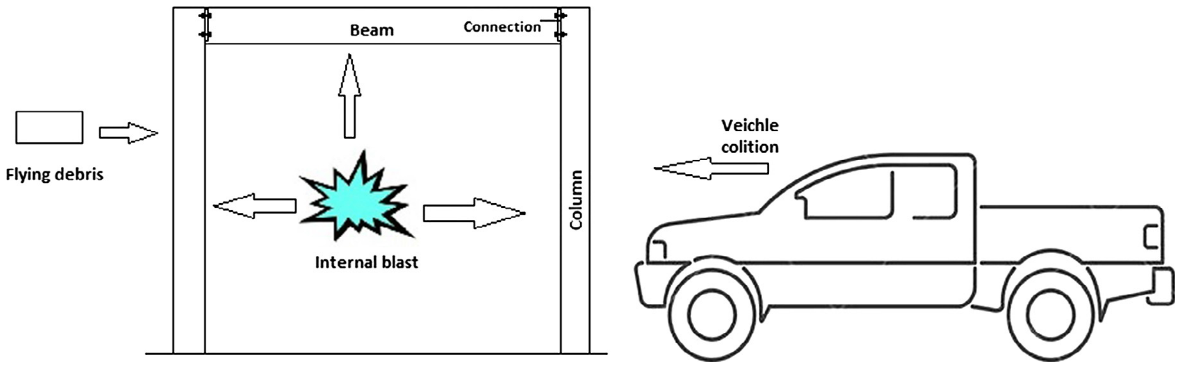

Fig. 1. The possible cause of a lateral impact.

to beams using suitable connections. Then, studying the columns response with ignoring the connection contribution would lead to incomplete understanding of the overall steel frame behaviour. Izzuddin et al. [11] realized this fact and concluded that progressive collapse failure of buildings is largely dominated by the maximum deformation allowed on the connections in relation to their built-in ductility.

The lack of knowledge on the dynamic capacities of steel connections indicates that limited studies were conducted. Recently, an experimental and numerical study on fin-plate connections under static and dynamic conditions was undertaken with a loading time to failure less than 32 ms. The study verified the ability of the modified component method to predict the connection response under high strain rate loading [12]. Wang et al. [13] also investigated numerically the response of a fin-plate connection due to falling floor impact loads. The main finding was the total displacement could be reduced using high strength steel. Angle cleat connections were investigated as another type of connection under high loading rate by Rahbari et al. [14] with the results indicating that such connections are relatively insensitive to the strain rate. A numerical study was presented by Kang et al. [15] as an attempt to investigate the response of steel frame with moment resisting connections against vehicle impact. The results showed that the frame remained stable under 40 km/h (11.1 m/s) car hitting speed, while the frame was severely damaged in a progressive manner when the car speed reached more than 80 km/h. Grimsmo et al. [16] conducted an experimental study at which extended end plate connections were tested under quasi-static and impact load hitting the column axially (i.e. shear and bending moment produced on the connection). The results showed that the connections tested behaved in a preferable manner and became more ductile under impact loads. However, Tyas et al. [17] showed that the PDEPC connection became less ductile under dynamic test compared to that under quasi-static one. This contradiction in the results from Tyas et al. [17] and Grimsmo et al. [16] indicates that more research need to be carried out on both connection types to improve the knowledge on this issue. It should be mentioned that the studies conducted by Rahbari et al. [14], Kang et al. [15] and Tyas et al. [17] were under lateral dynamic load while the others were under gravitational dynamic loads. The experimental study that carried out by Grimsmo et al. aforementioned at Ref. [16] was followed by a numerical study conducted by the same authors using the finite element modelling [18]. The main findings were that the energy dissipated by the connection was significantly increased by reducing the end plate thickness, while marginal effect on the response of the connection was found by applying different axial forces on beam.

In this paper, simple and semi-rigid end plate connections were investigated experimentally and numerically against static and impact loads applied laterally on the column. The experimental work contained testing eight L-beam to column connections, four of them under impact loads and the others under quasi-static load. The test set-up was designed to provide moment and axial tensile force at the connections. Moreover, finite elements models were developed and verified by the experimental results, which were further used to predict the internal forces and energies dissipated under static and dynamic loads. In order to present a relation between the static and dynamic behaviour of the connections, Dynamic Increase Factor (DIF) which is preferred by the structural engineers, was suggested to assist predicting internal forces generated on the connection due to impact loading based on forces and energy.

2. Experimental study

2.1. Reaction frame fabrication

The specimens to be tested require a stiff reaction frame to support them under both the quasi-static and impact loads. This frame should be stiff enough to minimize any movement during the test that may affect the results. The frame was designed and fabricated at the University of Liverpool and some trial tests were carried out to examine its suitability.

Fig. 2 shows the schematic diagram of the test setup containing the details of the frame, in which the frame contains three parts, i.e. floor mounted rails, moveable sub-assembly and bracers. The rails provided a fixed location for the drop hammer operator. Also, holes in the rails were provided to allow the movable sub-assembly for variable lengths. Two vertically mounted supports fabricated were bolted to the rails to provide a rigid base. The cross members with a detachable clamping setup provided a method to rigidly clamp the samples. Three rigid bracers were employed to connect the rails to both ends of the sub-assembly frame and the detachable clamping setup in order to minimize the rotational movement of the sub-assembly frame which supports the specimens.

The rigidity of the reaction frame was examined prior to test the specimens. Hence, three additional trial specimens having a connection stronger than all of those to be investigated in this study were tested under impact load. The translational and rotational movements of the reaction frame at the detachable clamping where the specimen connected to the stiff frame were recorded using high speed camera. The maximum rotational angle and the maximum downward translation of the detachable clamp for all trials measured were 0.61° and 1.7 mm, respectively. However, it is expected that this error is to be minimized using weaker joints as proposed in this study.