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Dynamic behaviour of web cleat connections subjected to sudden column removal scenario

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A R T I C L E I N F O

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A B S T R A C T

In this paper, experimental tests and numerical analyses were carried out to investigate the dynamic behaviour of web cleat beam-column connections subjected to sudden column removal scenario. In the test programme, different magnitudes of uniformly distributed loads were applied at the two-side-beam spans which were connected to a middle column with double angle web cleat connections on both sides of the central column. Both dynamic and static tests were conducted to gain a better understanding of the dynamic effects on structural performance. Test results showed that the maximum displacement of the web cleat connections under sudden column removal would be significantly increased compared with the one under static loading condition. Both force- and displacement-based Dynamic Increase Factors (DIFs) were measured from the tests. Besides, a three-dimensional numerical model was developed using commercial finite element software ABAQUS which was validated by comparing with the experimental observed response. Based on the proposed finite element model, parametric studies on load release time were carried out. The dynamic response of the connections which was defined as the relationship between the initial support force of the middle column and the maximum dynamic displacement, was also investigated. The analyses results showed that the maximum dynamic load capacity of this web cleat connection was about 2.8 times lower than its static load capacity.

1. Introduction

The collapses of Alfred P. Murrah Federal Building USA in 1995 and the New York World Trade Centre in September 2001 due to terrorist attack have generated a new wave of interest in research to resist progressive collapse. With the advancement in technology, modern buildings become taller, lighter and more flexible. This highlights the pressing need to consider progressive collapse mitigation as a basic design criterion due to significant casualties and economic losses when a building collapse occurs. Progressive collapse is a complex dynamic process with high geometric and material nonlinearities. Structural response to the initial damage of a column under an extreme event involves transient dynamic behaviour, vibration of building elements and redistribution of unbalanced internal forces. Thus, dynamic effect is one of the most important factors in ascertaining whether the initial triggering damage may lead to a partial or total collapse of a building.

Considering the dynamic behaviour associated with extreme loading events, sudden column removal is deemed as an appropriate design scenario on alternate load path approach. For mitigation of progressive collapse, this approach has been advocated by a number of researchers to ascertain progressive collapse resistance [1,2] and is also recommended in the two most recent design guidelines GSA 2003 [3] and DoD 2010 [4] proposed in the USA. In GSA 2003 [3], the dynamic effects of sudden column loss are considered by using an equivalent static load multiplied by a constant dynamic increase factor (DIF) of 2.0. It is believed that the value of 2.0 may lead to a conservative design of buildings against progressive collapse [5]. A significant improvement made in DoD 2010 [4] is that the DIF is no longer a constant factor of 2.0, but is dependent on the connection type and the associated plastic rotation limit (ductility). However, mechanisms such as compressive arch action and catenary action, are not explicitly considered in DoD guidelines [4]. Besides, it appears that the proposed DIF to be used in static analysis to simulate dynamic response does not come from actual dynamic tests. In order to identify the different resistance mechanisms and the associated DIF, a simplified framework for progressive collapse assessment of multi-storey buildings has been proposed by Izzuddin et al. [6] through considering sudden column loss as a design scenario. Based on the principle of energy balance, the proposed analysis treats nonlinear static response incorporating the dynamic effects in a simple way. Analytical results from Izzuddin and Nethercot [7] demonstrate that the DIF increases with structural ductility if catenary action in beams or membrane action in slabs is taken into account.

So far, very limited experiments have been conducted on the dynamic response of structural sub-assemblies to progressive collapse. In 2007, an experimental work was carried out by Sasani et al. [8] to study an actual 10-storey reinforced concrete (RC) structure following the implosion of an exterior column. The displacement-time history of

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the joint just above the missing column was captured and potential failure modes were discussed. However, since no live loads were incorporated into the test, the maximum vertical displacement was only 7 mm. There were only limited discussions on the differences between the dynamic and the static responses for the experimental study.

As a matter of fact, most of the current experimental works related to progressive collapse were based on quasi-static tests to investigate some important mechanisms such as catenary action or membrane action to mitigate progressive collapse of buildings. Yi et al. [9] tested a four-bay, three-storey and one-third scale model under static loading condition to investigate the progressive failure of a reinforced concrete frame due to the loss of a lower storey. It was found that the RC frame experienced three distinct phases in its response to progressive collapse: elastic, plastic, and catenary phases. It should be noted that Yi et al. [9] emphasised the urgent need to conduct a more sophisticated dynamic test.

Besides, with the recognition that the joint is a key parameter for maintaining structural integrity under abnormal loads, extensive studies have been carried out focusing on the joint behaviour under catenary mode. A substructure experimental test and five beam-column joint tests were conducted by Demonceau et al. [10] to observe the structural performance at catenary action stage and to obtain the moment-tension force interaction curves of composite joints. Recently, Yang and Tan [11] conducted a series of tests with the aim of investigating the load capacity and ductility of different types of commonly used steel connections subjected to catenary action. The connection response was studied by applying a point load at the location of the middle column until the connection totally failed. Regarding the behaviour of simple connections, the test results showed that web cleat connection had the best performance in developing catenary action [11]. However, without considering the dynamic effect, the resistance of connections obtained from monotonic static loading condition may be unsafe. Furthermore, the ductility of connections, which has significant effect on structural response to progressive collapse, may also be reduced due to dynamic effect. This phenomenon cannot be simply investigated using static pushdown tests alone.

In this paper, experiments and numerical analyses have been carried out to investigate the dynamic behaviour of steel double angle web cleat connections subjected to sudden column removal scenario. Of particular concern was the response of middle beam-column connections just above the "missing" column. A quick release mechanism was employed to simulate the sudden column removal scenario. In the test programme, the geometry of the specimens remained unchanged. Four different values of uniformly distributed load were applied along the two beam spans connected to a middle column with web cleat connections. Both dynamic and static tests were conducted for a better understanding of the dynamic effects on the structural performance. Therefore, a total of eight tests were carried out at the Protective Engineering Laboratory of Nanyang Technological University. The load-release time, the displacement time history, as well as redistribution of internal forces were investigated. Both force- and displacement-based Dynamic Increase Factors (DIFs) were evaluated. Thus, the experimentally obtained DIFs can be compared with the code-recommended values in DoD guidelines [4].

Following the experimental programme, finite element analyses were conducted in order to simulate the structural responses of the tested specimens. Three-dimensional numerical models employing solid elements were developed using a commercial software ABAQUS and validated by the experiments. Based on the calibrated numerical models, parametric studies were then carried out to analyse the experimental results for a wider range of parameters (i.e. the load release time, different applied loads, etc.). Furthermore, the finite element model is useful for a comprehensive numerical investigation on the dynamic behaviour of other bolted connections, e.g. fin plate connections.

It is worthy to be mentioned that the sudden column removal scenario, as an idealized design approach for progressive collapse assessment, may not be able to represent all of the realistic phenomena of structural collapse due to blast loading. McConnell and Brown [12] evaluated the effectiveness of this design scenario in resisting the real blast threats. By studying the responses of steel columns subjected to different intensities of blast loads, it was concluded that the sudden column removal scenario was typically representative of design situations with relatively small charge sizes. For large charge sizes, it may result in the failure of multiple columns. This would make the one-column removal based progressive collapse analysis highly un-conservative. Besides, Shi et al. [13] pointed out that the column removal scenario ignored inevitable non-zero initial conditions since damage on adjacent structural members may be induced by the blast loads. However, the main objectives of this study are to provide a comparison of the connection response due to dynamic effects, and to improve the current column-removal-based design approach in DoD 2010 [4]. In addition, the observed connection response in this paper will be used for the validation of component-based joint models proposed in future studies. The joint models will be useful for the development of numerical models for analysis of structural buildings to progressive collapse, which may incorporated the initial damage conditions associated with a blast event.

2. Test programme

2.1. Test setup and load procedure

In this experimental study, the focus was on the behaviour of the middle connections just above the missing column. In order to simplify the test arrangement, the two beam ends were simulated using pin conditions to model the contra-flexure points located approximately at the mid-span of each beam. The main idea of the dynamic test is illustrated in Fig. 1. Firstly, the specimen was preloaded with a uniformly distributed load (UDL) and the middle connection was supported by a quick-release mechanism to simulate the support of a column. Then the mechanism was suddenly released manually to simulate the sudden column removal scenario which caused the middle connection to undergo large vertical deformations within a very short period of time.

Fig. 2 shows the quick-release mechanism employed here as well as the 'unloading' procedure. The mechanism has a load capacity of up to 300 kN, which can be released by manually jerking down a

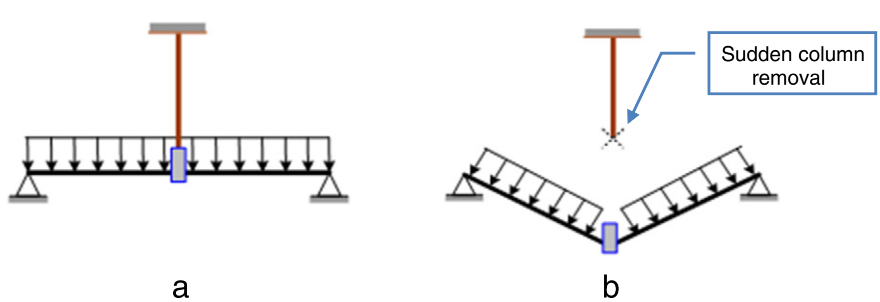

Fig. 1. The test programme on beam-column middle connections subjected to sudden column removal scenario.