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Strengthening of precast RC beam-column connections for progressive collapse mitigation using bolted steel plates

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ABSTRACT

Being one of the most critical scenarios in extreme events such as blast attacks, the progressive collapse of reinforced concrete (RC) structures has attracted the attention of structural engineering community. As precast concrete buildings are deficient in structural continuity, they are more vulnerable to progressive collapse than cast-in-situ RC buildings. Hence, effective rehabilitation techniques to upgrade beam-column joints in existing precast RC buildings for progressive collapse mitigation are needed. The goal of this study is to investigate the effectiveness of using bolted steel plates on the behavior of precast beam-column connections under sudden column-loss scenario. This study presents experiments involving one half-scale precast RC beam-column assembly, which represented the most prevalent types of existing precast beam-column joints in Saudi Arabia. One monolithic test specimen having continuity of top and bottom beam rebars was used for the sake of comparison. Another precast specimen similar to the control one was strengthened using bolted steel plates within the connection region. The progressive collapse scenario was simulated by removing the central column support and applying a sudden vertical load on this column at a rate of 100 mm/s until failure. The collapse load of both monolithic and strengthened specimens was predicted using a simplified section analysis procedure. The analysis was then used for some useful parametric studies in which the effect of different steel plate parameters on the response of test frames under middle column-loss scenario was investigated.

1. Introduction

In the last few decades, precast construction has become common in Saudi Arabia because of its high speed of construction. Buildings are extremely vulnerable to progressive collapses due to the loss of one or more columns caused by accidental events such as blast attacks. It is, therefore, important to study the behavior of precast concrete structures for progressive collapse to avoid catastrophic events. As precast buildings lack structural continuity and redundancy in the load paths, they are even more susceptible to progressive collapse than cast-in-situ monolithic buildings. Hence, effective and economical rehabilitation techniques to upgrade beam-column connections in existing precast concrete buildings for progressive collapse mitigation are needed.

The behavior of different types of precast RC beam-column joints has been investigated by numerous researchers [1–5]. In these studies, different designs for precast joints were studied which included: (i) connections using dowel rebars, (ii) dowel rebars with steel cleat angles, (iii) steel cleat angles with stiffeners, (iv) tie rods and steel plates, (v) use of cast-in-situ concrete in beam-column connection, (vi) bolted connections, (vii) composite connection with welding, etc. In these studies, the behavior of precast connections was evaluated in terms of load-displacement characteristics. The performance was then compared with their monolithic counterparts.

Savoia et al. [6] presented a complete and commented collection of cases of damage and collapse in precast concrete industrial buildings, observed during a series of field surveys after the 2012 Emilia earthquake in Northern Italy. They were selected among a total of about 2000 industrial RC precast buildings, whose structural characteristics and damage have been collected in a large database by the authors. The main causes of the collapses were vulnerabilities related to the structural characteristics of Italian precast buildings not designed with seismic criteria. In particular, these structures were typically built as an assembly of monolithic elements (roof elements, main and secondary beams, columns) in statically determinate configurations. The most common failure causes identified were: the absence of mechanical connectors between precast monolithic elements, the interaction of

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structural elements with nonstructural walls, the insufficient column bending capacity, the rotation of pocket foundations, the inadequacy of connections of external precast cladding walls to bearing elements (columns and beams), and the overturning of racks in buildings used as warehouses or in automated storage facilities.

One of the approaches to evaluate progressive collapse is to study the effects of sudden removal of vertical load-carrying members (such as a column) on the rest of the structure, and to check if any other alternate load paths do exist thereby arresting the damage initiation from propagating from one element to another. This notional column removal scenario adopted in many design codes and guidelines [7–12] is based on similar incidents occurred in the past such as the progressive collapse of a 22-story precast concrete apartment building at Ronan Point and the Alfred P. Murrah Building in Oklahoma City as result of an explosion [13,14]. There are many other examples of progressive collapse of buildings due to the damage of columns as result of vehicular impact such as the collapse of a building in New York City [15] and the parking structure of Isle of Capri casino [16]. Research on progressive collapse of structures was conducted by Peakau and Cui [17], Almusallam et al. [14,18], Allen and Schriever [19], Elsanadedy et al. [20], Baldridge and Humay [21], Choi and Chang [22], Al-Salloum et al. [23], Dat et al. [24], Bao et al. [25], and others. Kang and Tan [26] carried out an experimental study to investigate the behavior of precast RC beam-column test specimens under column-loss scenario. The beams and columns were joined together by cast-in-situ concrete topping above the two adjoining beams and the joint. The top longitudinal rebars passed through the joint continuously. The middle joint detailing involved 90° bend and lap-splice of bottom rebars. The specimens were tested to failure under quasi-static loads. It was concluded that the continuity of top reinforcement along with the cast-in-situ concrete topping led to the development of compressive arch action (CAA) and catenary action. However, the CAA and catenary action capacities were overestimated due to the rigid boundary conditions adopted in experiments.

In the past few years, a substantial research has been conducted on strengthening of deficient monolithic RC beam-columns joints using different techniques such as concrete jackets [27], steel jackets [28], fiber reinforced polymer (FRP) sheets [29–31] and textile reinforced mortar (TRM) strengthening [32]. However, strengthening of existing precast beam-column connections is a challenging task, which poses many practical difficulties. Da Fonseca et al. [33] carried out an experimental study on a small-scale precast concrete frame, comprising of two precast columns and one beam. The frame was loaded in two points of the beam until the cracks were observed in the beam. The beam-column joints were then strengthened using near surface mounted (NSM) CFRP strips embedded in the lateral concrete cover. The strengthened frame was reloaded until failure. Strengthened connections exhibited semi-rigid behavior and provided significant reduction in the beam mid-span deflection.

Gopinathan and Subramanian [34] studied experimentally the behavior of precast concrete frames under lateral loading. Two 1/4th scale, three-bay, five-story frames were cast. The first frame was monolithic that has been used as baseline for comparison; whereas the other one was precast RC frame. The beam-column joints in the precast frame were strengthened by specially designed steel bolts and L-angles via welding and bolting. The frames were subjected to lateral cyclic load until failure. The efficiency and performance of beam-column joints were studied and the behavior of precast frame was compared with the monolithic one. The ultimate base shear of the precast frame was about 90% of that of the monolithic frame. However, the story drift of the precast frame was 30% more than that of the monolithic frame.

de Freitas et al. [35] studied experimentally and numerically the use of bonded steel plates system and the sandwich steel plates system for stiffening the existing orthotropic bridge decks (OBD) for reducing the stress at the fatigue-sensitive details and thus extending the fatigue life of the decks. The reinforced deck panels were tested using realistic wheel loads. The results showed at least 40% stress reduction close to the fatigue-sensitive details in the reinforced decks. The two suggested reinforcement systems were shown to be the efficient lightweight solutions for stiffening the orthotropic bridge decks.

A search of literature indicates that even though there is considerable research on strengthening of monolithic RC beam-column joints using different techniques, but work on rehabilitation of precast RC beam-column connections is very limited. In fact, significant work on strengthening of precast RC beam-column joints for progressive collapse mitigation could not be found in the approachable references. Precast structures are widely used in residential and commercial buildings throughout the world. As a result, any collapse of precast structures would result in huge losses of life and property. For this reason, it is necessary to conduct research on the progressive collapse performance of precast structures and suggest methodologies to improve their behavior under such scenarios.

As mentioned previously, research on the progressive collapse potential of strengthened precast concrete beam-column connections could not be found. The lack of such research creates a challenge for such studies. The goal of this research is to investigate experimentally and analytically the progressive collapse risk of precast concrete beam-column joints strengthened using bolted steel plates. The progressive collapse was simulated in the testing by middle column loss scenario. In order to study the effectiveness of the strengthening technique, the results of the strengthened specimen were compared with both a reference unstrengthened precast specimen, which represented the most prevalent types of existing precast beam-column joints in Saudi Arabia, and a monolithic specimen with continuous top and bottom beam rebars.

2. Experimental program

2.1. Test matrix

The experimental program includes testing up to collapse a total of 3 half-scale beam-column connection sub-assemblages under vertical cyclic loading so as to provide the equivalent of severe progressive collapse damage. Details of the three test specimens are given in Figs. 1–3. It should be noted that in the designation of test specimens, the acronyms "PC" and "MC" denote precast concrete and monolithic concrete, respectively, the letters "C" and "S" symbolize control and strengthened specimens, respectively, and the acronym "SMF" stands for special moment frame with continuous top and bottom beam rebars. Out of the three specimens, the first one (PC-C) was an as-built control precast concrete specimen. This specimen was designed to represent the most common type of exiting precast beam-column connections in Saudi Arabia. Precast specimen PC-C was prepared with beam and column members cast individually and then assembled on test bed as is the norm in the field. The second specimen MC-SMF was monolithic with continuous top and bottom beam rebars through the joint region. The third beam-column connection specimen PC-S was the same as the precast control specimen, but it was strengthened using bolted steel plates within connection region. All specimens consisted of two-bay beams and three columns and were subjected to vertical dynamic loading that simulates a column-removal scenario due to extreme events such as blast attacks. The efficiency of the rehabilitation scheme was evaluated by comparing the experimental results of the tested specimens in terms of their mode of failure and load-displacement characteristics.

2.2. Test specimen details and assembly

The test specimens were designed to be half-scale of a prototype perimeter frame. The selected two-bay prototype frame was assumed to be a part of an eight-story commercial precast building located at a busy intersection of Riyadh. In the prototype building, the spans in both the