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Nonlinear Cyclic Behaviour of Precast Concrete Frame Sub-Assemblies With "Dry" End Plate Connection

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ABSTRACT

This paper presents in detail the design characteristics of dry and demountable end plate beam-column connection for an emulative jointed precast concrete frame system whose structural performance is similar to that of a wet jointed/monolithic concrete frame system. The load transfer mechanism as well as an analytical framework to calculate the ultimate capacity of the end plate connection is explained in detail. The hysteretic behaviour of the frame sub-assemblies with the end plate connection is experimentally evaluated under quasi-static cyclic loading. Accuracy of the developed analytical equations is assessed by comparing the predicted nominal lateral strength and stiffness with the test results. Also, structural performance of a frame sub-assembly with the end plate connection is evaluated by comparing the experimentally obtained hysteretic plot with the hysteretic plots of the frame systems with wet joints or ductile connectors reported in literature. Nonlinear cyclic behaviour of the tested frame sub-assemblies is numerically simulated by using the "pivot" and "IMK peak oriented" hysteresis models, and the accuracy of the developed numerical models is evaluated by comparing with the test results. The importance of a correct moment-rotation backbone curve to capture the capping point is highlighted through different case studies. Based on the evidences reported herein, it is concluded that the proposed end plate beam-column connection acts as a rigid moment connection, and a precast concrete frame system developed using end plate beam-column connections is demountable and it is able to structurally perform at par with (if not better than) a precast concrete frame system with wet joints.

1. Introduction

1.1. Background

Precast concrete frame building systems are broadly classified into two categories; (i) equivalent monolithic/emulative systems, and (ii) jointed/non-emulative systems [1]. Nonlinear cyclic behaviour of an emulative precast concrete frame system is same as that of a monolithic concrete frame system, whereas it is not necessarily the case with the jointed frame system. An emulative precast concrete frame system is developed either using wet joints or bonded tendons [2]. Schematic representation of one such emulative frame system developed using U-shaped precast concrete beams and wet joints is shown in Fig. 1a [1,3,15]. In jointed/non-emulative precast concrete frame systems, the beams and columns are connected by using un-bonded tendons or steel connections [4–7]. Nonlinear cyclic behaviour of a jointed frame system developed using post-tensioned un-bonded tendons is ductile with minimal residual displacement [8,9]. In the past three decades, many steel connection configurations have been developed to connect precast concrete frame components and most of them rely on dowel action (i.e. shearing or bearing of the bolts) for the force transfer between beams and columns [4,10]. Such a non-emulative beam-column corbel connection using steel angles and dowels is shown in Fig. 1b [10]. Many precast concrete buildings with such corbel connections have been reported to be damaged in the past earthquakes, mainly due to failure of the dowels and inadequate seismic detailing in the beam ends [11]. Recently, experimental tests have been performed on corbel connections with different detailing to understand their different possible modes of failure [7,11]. With the improved seismic detailing, corbel connections were found to exhibit a stable shear versus deformation hysteretic behaviour. Another non-emulative jointed frame system in which the beams and columns are connected using ductile rods (embedded into the column) and steel billets is shown in Fig. 1c. Cyclic behaviour of such frame systems is characterized by severe

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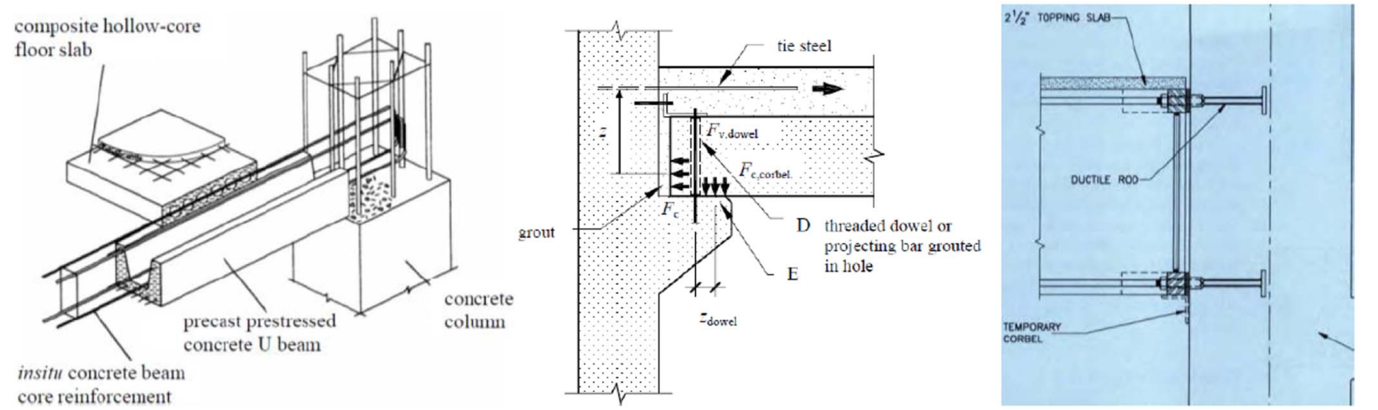

(a) Emulative wet joint [15] (b) Non-emulative corbel joint [10] (c) Non-emulative ductile rod joint [12]

Fig. 1. Examples of emulative and non-emulative precast concrete frame systems.

pinching [12]. Based on the past experimental observations, most existing precast concrete beam-column connections made of steel are classified as either semi-rigid or nominal pin connections (not as an emulative moment resisting connection) [4,5,7,10,13,14].

Construction speed of such precast concrete buildings is limited primarily due to numerous on-site activities such as setting up of formwork, casting and curing of wet joints and floor slabs, and grouting of ducts and connections etc. Both emulative and non-emulative frame systems turn into partially or fully monolithic units. Consequently, when such a building is obsolete in function or if some of its components suffer irreparable damage in an earthquake, the whole building will have to be demolished with no possibility of dismantling and reusing the undamaged components. The demolition process itself is environmentally unfriendly and results in unnecessary wastage of building materials. The demolition waste amounts to 17% and 40% of the landfill waste in New Zealand and Australia respectively [16,17]. Demolition of a concrete building is time consuming and requires careful planning to avoid any hazard to nearby structures. As the monolithic buildings are not structurally adaptable (i.e. not possible to replace the damaged components or not easy to add the new components), a repairable monolithic building requires considerable downtime to restore its functionality mainly due to the time involved in decision making about the condition of the damaged components, the time required to evaluate the residual capacities of the damaged components and identify an appropriate repair/retrofit strategy, and the actual repair/retrofit time. As a result, the occupancy interruption in such buildings after a moderate/major earthquake becomes substantial and untenable in many cases [18]. These issues associated with monolithic concrete frame buildings can be addressed with an emulative jointed precast concrete frame system with fully removable “dry” joints, which makes the building demountable and repairable/replaceable.

Very limited research has been carried out in development of demountable concrete building systems, mostly in non-seismic regions (i.e. extensively in Netherlands) [19–21]. A demountable flat slab building system made up of precast concrete slabs and columns to transfer the gravity loads to the foundations was developed and implemented in Netherlands [20,22,23]. To facilitate the removal of the building components, five different types of slab to column connections were developed, one such connection (referred as CD-20 system) developed by inserting the protruded dowels of the columns into the slotted holes of the slabs is shown in Fig. 2a. The seismic performance of this demountable flat slab building system was not experimentally investigated (as it was not developed for an active seismic region), and it appears that this building system will exhibit limited seismic resistance because of weak connections (i.e. no continuous load path between the connection and precast components). In active seismic regions, the design of structures focuses mainly of life safety during major earthquakes and the ease/difficulty of deconstruction of a building is not accounted for at all. Hence, more research is needed to develop a seismically robust demountable building system and create awareness of its benefits to the public [24]. In Japan, a demountable frame building system with flexible floor plan and post-tensioned tendons was built, which is shown in Fig. 2b [25]. The structural system of this demountable building is similar to that of a non-emulative jointed frame, and it requires careful removal of pre-stressed tendons before removal of the frame components. Few partially demountable car park buildings relying on either steel braces or cast-in-situ shear walls to resist the lateral loads have been designed and built in New Zealand [26,27]. The frame system of one of these buildings was developed by welding the precast concrete spandrels to the slender columns as shown in Fig. 2c. The main observations with the existing demountable concrete buildings are [3,28–32]; (i) some systems require partial demolition of the cast-in-situ components or cutting of the welded joints before dismantling the precast concrete components, (ii) non-emulative frame systems relying on other lateral load resisting options, and (iii) not structurally adaptable (as it is not possible to replace the damaged components) either because of the constraint in the degree of movement or global pre-stressed tendons.

To address the issues associated with the conventional and existing demountable precast concrete frame buildings, the authors have developed an emulative jointed precast concrete frame building system which is easy to erect/construct and demount, and remove/replace the components. Full details of the proposed demountable frame system, possible removable steel connections between its structural components, process of erection and demounting of a hypothetical building, demonstration of structural adaptability and upgradability in different possible scenarios is detailed in the literature [33–35]. The primary objectives of the research reported in this paper are; (i) to develop a dry and demountable end plate (EP) beam-column connection for an emulative jointed precast concrete frame system, and investigate the hysteretic behaviour of the frame sub-assemblies with the EP connection under quasi-static cyclic loading, (ii) to understand the failure modes in the precast concrete beams with the EP connection at different stages of lateral drift, (iii) to check whether the structural performance of the frame sub-assembly with the EP connection can be compared against the structural performance of the frame sub-assembly with the wet joints or ductile connectors, (iv) to investigate the replaceability aspect of the frame-assembly; replacing a damaged beam with an identical new beam and achieving structural performance similar to the original frame sub-assembly, and (v) to develop numerical macro-models that can reliably simulate the cyclic behaviour of frames with