CHAPTER 1

INTRODUCTION

1.1 Introduction

In the construction industry, the challenge is always about the speed and cost of the performance. Precast concrete, as a construction method, ensures high quality control, and durable, fast and economic buildings compared with cast in situ construction; therefore, it is widely used as a proper alternative to the latter.

The efficiency of precast concrete structures in resisting gravity or lateral loads relies on the behaviour of jointing systems including beam-column connections. The connection configuration and response including strength, rotational stiffness and ductility affect building frames in several ways. For instance, under gravity loads, the beam-column connection response affects mostly the behaviour of adjoining beams, while under lateral loads it affects the moment-distribution and the global stability (2^{nd} order effects).

Beam-column connections should be designed to transfer all types of forces: compression, tension, shear, bending and torsion. This could be achieved by ensuring a proper assemblage of joined members, and adequate continuity of the reinforcement. However, this goal is not easy because the design should take into account the simplicity and the practice of making the connections. Therefore, it is essential to consider both requirements of structural performance and buildability within the design of connections.

Among the connection types used in practice, the discontinuous (in construction terms only) precast concrete beam-column connection has been used in the precast concrete industry for many years in braced systems (Figure 1.1). This connection configuration is also called '*beam to column head connection'* according to *fib* (2011). It has advantages over other jointing methods as it is simple, needs no corbels, bolting or welding, and is efficient in providing reasonable continuity between adjoining elements. However, it still requires a generous tolerance for construction, which is related mainly to the process of housing the dowel bars protruding from the bottom column in preformed sleeves in the beam and top column, which could reach ±12.5 mm according to ACI (2008b).

Figure 1.1 Discontinuous beam-column connection used in a braced frame car park project – Preconco Ltd., Barbados, 2010

1.2 Problem statement

Despite the use of the discontinuous precast concrete beam-column connection in practice, no design rules or guides were found within the available sources. In addition, the connection configuration used in practice (see the car park building in Figure 1.1, for example) does not offer any beam-end negative (hogging) moment resistance capabilities for dead loads. This is because the continuity bars at the top of the beam are provided later within the topping concrete, meaning that the moment continuity is only active for imposed loads (*fib*, 2011), even though, in most cases, this feature is not considered in the design and the beam-ends are treated as pinned connections.

Also, in the practical detail (Figure 1.1), the gap between the beams is too narrow for the infill grout to be structural, and therefore the load transfer in compression will be forced to pass through the dowels in the head of the lower column, something for which it is not designed.

Based on the above-mentioned observations, there is scope to modify the discontinuous beam-column connection behaviour and to establish main design principles. The modifications in the connection configuration include (Figure 1.2):

- locating the continuity top bars within the precast concrete beams and casting the trough before constructing the slab. This is to provide beam-end hogging moment resistance capacity under dead loads, which counterbalances reversals of positive (sagging) moment generated under sway loads;
- using a new connection reinforcement detail under gravity loads to strengthen the connection, limit the crack width within the connection zone and move the final damage to a point outside the connection zones. The new reinforcement detail also includes bending the beam bottom bars around the column dowel bars to mobilise beam-end sagging moments under sway loads;
- grouting the vertical joint between the beams to provide a direct path to transfer the compressive stress in the beam.

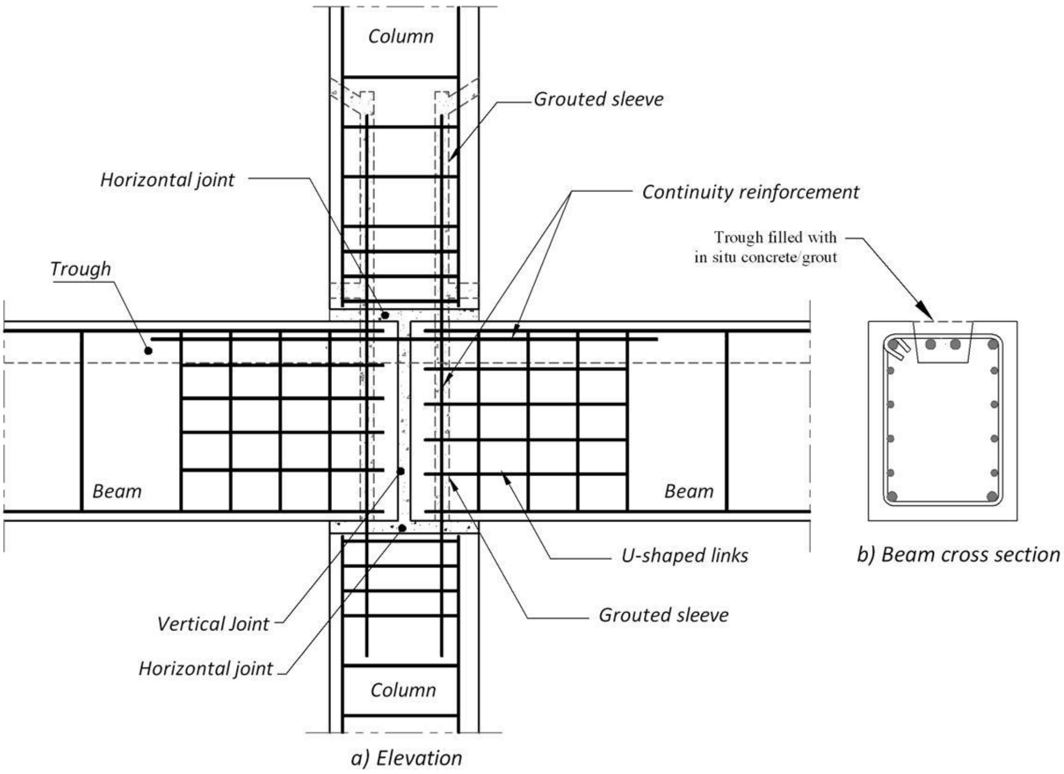

Figure 1.2 Proposed discontinuous beam-column connection configuration

1.3 Hypotheses

The hypotheses of the current study with respect to the discontinuous beam-column connection are: (i) the full beam-end hogging moment capacity can be mobilised as a result of providing continuity in the beam top reinforcement and altering the reinforcement details; (ii) the interaction between the beam bottom bars and the column bars provides the dowel action mechanism required to mobilise the beam-end sagging moment.

1.4 Aims and objectives

The aims of the current study are to:

- determine the effects of connection reinforcement details on the moment continuity across the connection;
- develop the basis for establishing main design principles for the connection type investigated in the current study.

In order to achieve the aims of the study, the following objectives are set.

- To determine experimentally the thickness and status of the joints within the connection needed to be used in the full-scale tests.
- To determine experimentally the effects of using different reinforcement details for the connection on the moment-rotation response (M-θ), crack propagation, crack width and the failure mode under separate gravity and sway loadings.
- To implement M-θ data in frame analyses to show the effects of the connection flexibility on the moment distribution and the sway.
- To calibrate simplified semi-rigid frame analyses that incorporate the effects of the flexibility of the beam-column connections.
- To establish a new approach for classifying precast concrete beam-column connections as rigid.
- To use the finite element modelling tool to replicate the experimental response of the connection.

1.5 Research methodology

For a reliable assessment of the behaviour of precast concrete beam-column connections, laboratory testing is recommended due to the complexity of the involved details (Catoia et al, 2008; Elliott et al, 1998; Loo and Yao, 1995) and to ensure that the connection has the necessary non-linear response characteristics (Ghosh et al, 1997). These complexities include: many contact regions of concrete-to-grout and steel bars-to-grout, possible irregularity in contact conditions, and construction initial imperfections, all of which restrict performing a straightforward analytical simulation for the connection. Therefore, before any attempt to develop analytical solutions for connections, experimental validation is required (Elliott et al, 2003b).

In this respect, the structural behaviour of the discontinuous beam-column connection will be examined by a mix of experimental and analytical methods using the following steps.

- Conducting preliminary small-scale biaxial loading tests to assess the ability of the connection to transfer axial loads with/without joint infill.
- Conducting full-scale beam-column connection tests subjected to separate gravity and sway loads taking the connection reinforcement detail as the main parameter.
- Performing semi-rigid frame analyses to find out the effects of the flexibility of the discontinuous beam-column connection in real frames.
- Modelling the semi-rigid behaviour of the connections tested under gravity loads using analytical and finite element modelling.

1.6 Limitations of the study

The investigation has been carried out by examining a full-scale beam-column using dimensions, reinforcement and beam and column loads resulting from a rigid frame analysis of a four-storey prototype building. The study moved towards modifying the connection to justify its use. Based on that, there are certain limitations in this study:

- the reported results are with respect to certain column and beam sizes and column axial load;
- the reported results are with respect to a certain range of concrete, grout and steel bar strength;
- in spite of using different continuity reinforcement within the connections whilst aiming to improve the behaviour, no attempts were made to investigate a wider range of reinforcement ratios;

- the rotational stiffnesses reported in the current study are with respect to the discontinuous precast concrete beam-column connection type investigated in the current study.

1.7 Behaviour of precast concrete beam-column connections

As connections in precast concrete construction are considered as the most critical locations in building frames, proper attention needs to be taken in designing them. CEB-FIP Model Code 1990 (1993) stated that, to ensure the performance of the precast concrete connections, the joints are required to:

1- accommodate the relative displacement required to mobilise the resistance of the joint;
2- resist all the action effects resulting from the analysis of the structure as a whole and from the analysis of the individual members;
3- secure robust and stable behaviour of the structure through the strength and deformability of the joints;
4- take into consideration the anticipated required tolerances during manufacture and erection.

1.7.1 Elementary behaviour

In ordinary frame analysis, beam-column connections are designed either as nominally pinned (free to rotate with no moment capacity) or fixed (zero rotation with definite moment capacity). This assumption does not match the actual practice even in monolithic construction, where there is a limited beam-column relative rotation (Baharuddin et al, 2008; Ferreira, 1999) that is not considered as a result of incomplete knowledge about moment-rotation behaviour or not having the required modelling tools.

In precast concrete construction, the beam-column connection could be categorised into simple (pinned) connections, which transmit purely shear forces, and moment resisting connections, which mobilise moments in addition to the shear. For design convenience, precast concrete connections are strictly dealt with as either pinned or fixed, in spite of the majority of the connections behave in a semi-rigid manner (Elliott et al, 2003b), which mobiles a certain amount of the beam moment depending on the connection stiffness. Further, the moment resisting connections could be divided into 'equivalent monolithic' systems, where the connections are stronger than the adjacent precast concrete elements, and 'jointed' systems, where the connections are weaker (*fib*, 2003).

The equivalent monolithic system (the connection type studied in this research is intended to be among them) could be either strong (with limited ductility) or ductile (with normal strength). In the first type, the connection is sufficiently stronger than the adjacent members and the connection remains in an elastic region while the yielding occurs elsewhere in the frame. In ductile connections, the connection is designed for the required strength but with sufficient ductility to ensure non-brittle failure.

1.7.2 Semi-rigid behaviour

In order to evaluate the rigidity of a connection under gravity loads, a beam-line analysis could be used, which provides a convenient way to determine the influence of the semi-rigid connection on the behaviour of an elastic beam.

To obtain the beam-line (Figure 1.3) for a particular single beam subjected to uniformly distributed load 'w', the moment-rotation diagram is constructed considering the extreme conditions. The first condition is a pinned beam to determine point A, which represents the rotation ($\frac{\mathrm{W\ L}^3}{24\ \mathrm{EI}}$) of the beam at supports under distributed load. The second condition is a fully-rigid beam to determine point B, which represents the hogging moment of the beam ($\frac{W\,L^2}{12}$) at the supports under distributed load. The line that connects points A and B is known as the “beam-line”.

In Figure 1.3, line 1 represents the behaviour of a fully-rigid connection, and line 2 represents the behaviour of an ideally pinned connection. To assess any connection, the moment-rotation plot needs to be verified against the beam-line. If a moment-rotation relation (e.g. line 3) fails to cross the beam line, then the connection is considered as pinned due to the lack of the exhibited ductility.

On the other hand, if the moment-rotation relation (e.g. line 4) crosses the beam-line, the connection will have sufficient ductility and achieve the required strength to be considered as a semi-rigid connection, and might be considered as a fully-rigid connection when the difference is negligible in comparison to line 1. For full assessment of plot 4, the classification limits for the semi-rigid zone given by the codes of practices need to be verified, which will be presented in detail in Chapter 2.

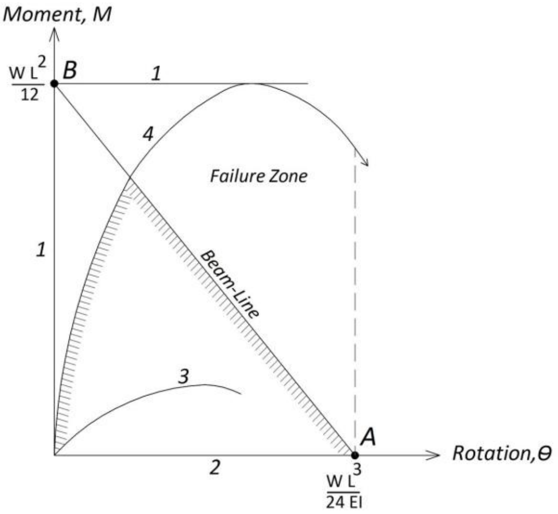

Figure 1.3 Moment-rotation characteristic of beam-column connections

1.7.3 Strong connection concept

As mentioned in Section 1.7.1, an equivalent monolithic beam-column connection could be achieved by designing the connection to be stronger than the adjoining members; the connection is designed to remain elastic while inelastic action takes place away from the connection. Beam-column joints should to be designed in such a way to force the failure to happen in the beam outside the joint (Hegger et al, 2004); it is especially advised to adopt this concept in buildings subjected to seismic loads (Ghosh et al, 1997; ICBO, 1997). The non-linear yielding region should be separated from the column by a distance not less than one half of the member's depth, as recommended by UBC code of practice (ICBO, 1997).

In the current study the concept of a strong connection has been used to strengthen the semi-rigid beam-column connection to control the crack width within the connection zone under gravity loads. This will guarantee avoiding yielding and slippage within the connection and move the final failure away from the connection.

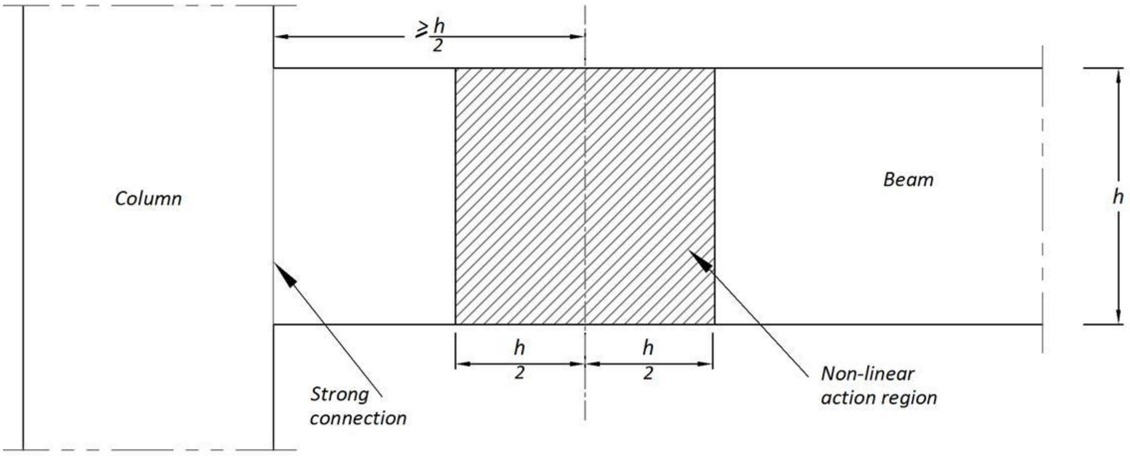

Figure 1.4 Non-linear action region and location (Ghosh et al, 1997)

1.8 Layout of thesis

This thesis structure is organised into nine chapters, as follows.

A) Chapter 1 introduces the research background and significance, in addition to the aims and objectives.

B) Chapter 2 presents the literature review related to the current investigation.

C) Chapter 3 presents the test set up and the results of the small-scale biaxial compression tests for beam-column connections.

D) Chapter 4 describes the test set up for the full-scale beam-column connection under gravity and sway loads.

E) Chapter 5 presents and discusses the results obtained from the full-scale tests under gravity loads.

F) Chapter 6 presents and discusses the results obtained from the full-scale tests under sway loads.

G) Chapter 7 introduces the finite element method with the application of the ANSYS software. This is to produce a 3D FE model simulating the semi—rigid behaviour of the connections tested under gravity loads.

H) Chapter 8 presents the analysis and design considerations for the tested beam-column connection configuration, including performing semi-rigid frame analysis using different techniques to quantify the sufficiency of the connection in real frames.

I) Chapter 9 highlights the main research findings, conclusions and recommendations, in addition to suggestions for further research.