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Development of a proposed design method for discontinuous columns in braced frames

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ABSTRACT

A column design method has been developed for use in braced frames with discontinuous columns using flexible cap and base plates and floor beams that are either simply supported or continuous. The proposed method is intended to be used with shallow floor construction with concrete or steel/concrete composite slabs in which the floor slab occupies the depth of the floor beams and is fully grouted to the beams so that the slab restrains the full depth of the beams. It was developed to simplify the design of square hollow sections discontinuous columns in frames using asymmetric beam (ASB) type floor construction. Floor beams are designed to carry the floor loads without interaction with the columns; columns are then designed to resist the floor beam reactions assuming a deformed shape derived from end-rotations equal to the slope of the floor beams at the top or bottom of the column, whichever is the greater. The method incorporates the elasto-plastic behaviour of columns subject to axial compression and large end-rotations and has been verified by physical tests on full-scale square hollow sections columns and finite element analysis using non-linear geometry and material properties and including residual stresses.

1. Introduction

In braced steel frame construction it is usual practice for a single length of column to extend over two or more stories and for the beams to frame into the continuous column and be connected by connections designed for vertical shear. Recently a new form of braced frame has been used in the UK for residential construction in which the columns are discontinuous [1]. Columns are fabricated in single storey lengths and fitted with horizontal plates (known as cap- or end-plates) at the top and bottom in order to bolt the column directly to beams below and above which are continuous over the column. Square hollow sections with the smallest possible size are used for the columns so that they can be hidden in the thickness of the walls. Because the beams are continuous, passing uninterrupted over the column lines, they benefit from the efficiency of continuity but without the extra fabrication cost associated with forming a full strength and rigid connection between discontinuous beams and continuous columns. The continuity of the beams across the tops of the columns induces rotation at the top and bottom of the column under some loading arrangements resulting in curvature of the column, which may reduce the resistance of the column below that of an equivalent pin-ended strut, and therefore a design method for this form of construction is required. A method has been published [2] but this uses nominal moments and does not explicitly consider the magnitude of the slopes of the beams at the top and bottom of the column. This paper describes the development and validation of a new design method for square hollow section discontinuous columns which is safe, gives economical column sizes and is easy to apply by designers.

1.1. Braced frames with discontinuous columns

A typical frame using discontinuous columns is shown in Fig. 1 (much larger frames than that illustrated have been constructed, up to 14 storeys high). Each column piece is only one storey high and to provide a shallow construction depth, the floor, which may be composite construction using deep profile decking or pre-cast concrete, is supported on the bottom flange of asymmetric beams. Being built-in between the beams, the floor stabilises the beams (provided that precast units are fully grouted). This type of construction has a number of benefits including shallow floor construction [3,4] and reduced building height, beam continuity achieved with inexpensive connections [1], slender columns that can either be hidden in walls (or are of low visual impact if not hidden) and safe, easy crane hook access when lifting in pre-cast concrete floor units or metal decking because the columns do not extend above the floor beams until the next storey is erected. Set against these benefits are the disadvantages of: the greater number of individual column pieces to lift, so more crane time for column erection is

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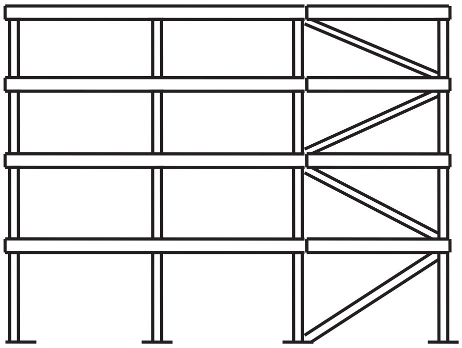

Fig. 1. Columns and beams in a typical frame with discontinuous column.

required; continuous beams give fewer pieces but greater piece weights, possibly increasing the crane requirements; column piece labelling is critical wherever different wall thicknesses of the same column sizes are used because all the columns appear to be identical but have different wall thicknesses; the design of the columns is problematic and guidance is required.

None of the design methods currently available are ideal for the design of discontinuous columns in braced frames. A new design method is required because (i) frame analysis with varying joint stiffness is too complex for routine design and (ii) methods based on nominal moments are uncertain and often give very conservative approximations. Research by Gent and Milner [5,6] and later by Davison et al. [7] and Gibbons et al. [8] demonstrated that the partial restraint inherent in nominally pinned columns is sufficient to increase the buckling resistance. (Readers interested in tracing the development of this work on 'moment shedding' are referred to Nethercot [9]). This earlier work suggested that it ought to be possible to devise a simple yet economic column design method for discontinuous columns. This paper details a study leading to the development of a proposed design method for square hollow section discontinuous columns in braced frames.

1.2. A new column design approach required

When considering the behaviour of discontinuous columns two factors are of particular interest (1) the rotational stiffness of the column-beam joint (2) the effect of bending moments in the columns on the compression resistance. The axial compression in the columns in the upper stories of a building will be relatively small and if thin cap-plates are used, the connections will be flexible so the beam can rotate relative to the columns. This would result in higher sagging moments in the beams than would be calculated in a rigid frame analysis. In the lower stories of a building, the larger axial compression clamps the columns and beams so that very little rotation of the beam relative to the column is possible, so the frame resembles a continuous one. Elastic analysis as a continuous frame requires the designer to either determine the stiffness of the joints accounting for the effect of axial compression or to specify cap-plates so thick that the joint is practically rigid even for low axial compression. The bending moments in the columns calculated by elastic analysis of a continuous frame can be of such a magnitude that they cause a significant reduction in the resistance to axial compression. Larger column sections are then required, increasing the bending stiffness further and attracting even more bending moment. This may lead to heavy columns, negating one of the attractions of the construction method i.e. to have small column cross-sections to allow them to be hidden in walls or limit the visual impact of exposed columns.

Modification of traditional design approaches, such as simple construction [10] where the columns are assumed to be pinned, or continuous construction [11] using elastic analysis of a rigid frame, are unsatisfactory. The former is potentially unsafe due to the effects of imposed end-rotations on the column which leads to reduced axial capacity; the latter requires heavy connections to realise the design assumptions and attracts too much moment to the columns which are desired to be kept small. A radically new approach is proposed in which the beams may be designed independently of the columns but the columns are designed taking account of the end rotation imposed on them by the slope of the beams.

The column design method exploits the moment-rotation relationship in beam-columns which (i) are subject to end-moments in the elastic domain but are not required to resist these end-moments to maintain static equilibrium of the structure and (ii) may be strained beyond the elastic limit.

Gent [5] and Gent and Milner [6] investigated the behaviour of columns under these conditions. Their test program applied moments to the end of the columns through a turnbuckle system (see Fig. 2(a)) in which the load relaxed as the end-rotation increased, thus the end-moment reduced as the curvature of the column increased. Initially the column was loaded by application of end rotations through the turnbuckle system. Next axial load was applied gradually up to failure of the column by buckling while the end-moments were measured. The end moments were seen to decrease as the axial compression increased, as shown in Fig. 2(b). This occurred because the axial compression had to be resisted by the column to maintain static equilibrium whereas the end moment did not need to be resisted to maintain static equilibrium because increasing rotation of the column end allowed the turnbuckle system to relax and reduce the applied end-moment. Gent referred to this behaviour as "moment shedding". The phenomenon was also seen in large scale tests conducted by Davison et al. [7] and Gibbons et al. [8] and was incorporated in a proposed design method [12].

This behaviour is not what is commonly assumed in the design of beam columns. The common assumption is that the end-moments calculated by elastic analysis must always be resisted together with the axial load. In many cases this is appropriate, especially where the:

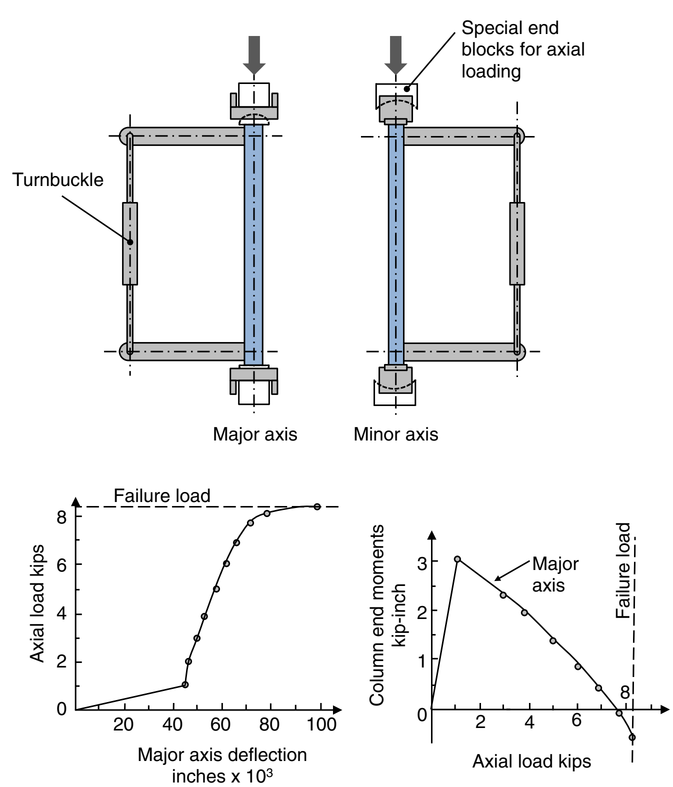

Fig. 2. Moment shedding from increasing axial load [6].