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Cross-section slenderness limits for columns with plastic rotations

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ABSTRACT

This paper reports on a study of local inelastic buckling in square hollow section columns with large plastic rotations. The study was conducted as part of the validation of a proposed design method for discontinuous columns in braced frames in which plastic rotations in the columns are used to limit the moments in the columns. The study included both testing of full-scale columns and a parametric study by finite element analysis. The results demonstrate that current codes permit cross section slenderness in plastic sections which are likely to lead to premature buckling in structures using plastic (inelastic) design if the rotations are large. Design limits are proposed for square hollow sections relating cross-section slenderness to column end rotations.

1. Introduction

A new form of braced frame has recently appeared in Britain for residential construction in which the columns are discontinuous [1]. Rather than passing over a number of storeys, each column is only one storey high and is fitted with a base and cap plate to bolt to the beams below and above, as shown in Fig. 1 [2]. Columns are square hollow sections with the smallest possible external size so they can be hidden in the thickness of the walls. The beams are continuous and pass over the top of the columns thus requiring little in fabrication yet benefitting from the efficiency of continuity. However, this continuity of the beams may cause some rotations to be induced at the top and bottom of the column under certain loading arrangements resulting in curvature of the column, which would reduce the resistance of the column below that of a pin-ended strut.

The behaviour of discontinuous columns is significantly affected by two issues (i) the stiffness of the column-beam joint and (ii) the effect of bending moments in the columns on the compression resistance. At the top of a building, the axial compression in the columns is small and if relatively thin column end-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. At the bottom of a building, the axial compression is high and this 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. If the frame is analyzed elastically as a continuous frame, the designer must either determine the stiffness of the joints (which means including the effect of axial compression) or specify end-plates so thick that the joint is sensibly rigid even for low axial compression. In a continuous frame, the bending moments in the columns calculated by elastic analysis can be of such a magnitude that they cause a significant reduction in the resistance to axial compression. To compensate for this, larger column areas are required, increasing the bending stiffness and attracting more bending moment. This may lead to heavy columns, negating one of the attractions of the construction method which is to have small column cross-sections to allow them to be hidden in walls or limit the visual impact of exposed columns.

The application of traditional design methods which might be used to design a frame with discontinuous columns is unsatisfactory for a number of reasons. For example, the use of the 'simple construction' method [3] (in which the beam is assumed to be supported by a cap plate) is compromised by the practical effects of using end plates of sufficient thickness to satisfy UK building regulations tying capacities. This necessitates the addition of a moment in the column arising from the column end rotation induced by the beam rotation (the stiffer the connection the greater the column rotation) and the resulting calculated column capacities are relatively low. If joints are assumed to be rigid and elastic analysis is used, the column end moments will be large thus lowering the calculated column capacity and relatively expensive connection details will be required to be consistent with the analysis model. To analyze such frames rigorously taking into account joint flexibility requires considerable effort, making them economically unattractive to design offices. Other methods of design might include designing the frame plastically (provided it is braced independently) and allowing plastic hinges to develop in the columns [1,4] or allowing for the semi-rigid nature of the joint in an approximate manner. In reviewing available methods, early

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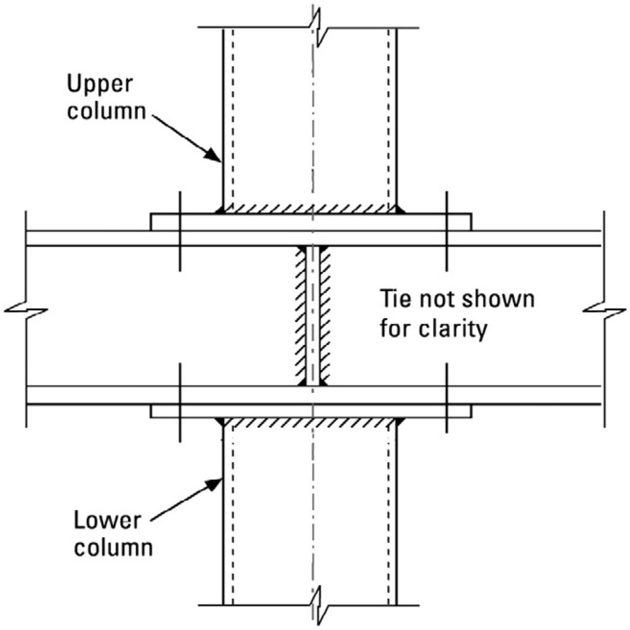

Fig. 1. Typical column-beam connection in discontinuous construction.

work by Gent and Milner provides an interesting approach, which is briefly outlined next.

1.1. Gent & Milner's column research

Gent published a paper in 1966 [5], followed by a second with Milner in 1968 [6], describing tests on small scale steel I-section columns subject to an initial end-rotation and then to increasing axial compression while the end-rotation remained applied. In the tests, end rotations were imposed at the two ends of the columns by moments applied through short cantilever beams loaded at their ends through a turnbuckle arrangement, as shown in Fig. 2(a). Importantly, this system allowed the moment to *reduce* as the column ends rotated, just as the end moments of a fixed-ended beam reduce if the end restraints are allowed to rotate. Initially the column had no axial load applied. The axial load was then increased and the end moment resisted was measured. The experiments showed that as the axial load was increased, the yielding of the column allowed such large end rotations that the columns "shed" the moments, as shown in Fig. 2(b).

As the axial compression was increased the end moments reduced to zero and then changed to acting in the opposite direction to some small amount before the member failed by flexural buckling in the plane orthogonal to the plane of the web of the column, even when the end rotations were applied in the plane of the web. It is important to note that the end moment was applied by the turnbuckle system — it was not applied as an eccentric load on the column; application as an eccentric load does not allow the moment to reduce as the column ends rotate and this is the design case assumed in codified checks of resistance to combined axial compression and bending.

Gent and Milner's tests showed that at the Ultimate Limit State in braced frames with rigid beam-column connections plasticity in the column reduced column stiffness thus limiting the bending moment attracted to the columns and also permitting more severe curvature in the columns. When moments are applied to the columns by the beams, the reduced column stiffness allows increased rotation of the column ends, tending to shed the applied moments provided that the beams can resist the moments shed by the columns. Gent and Milner [6] observed "that even under biaxial bending restrained columns have a remarkable capacity to sustain high axial loads by shedding end moments". Gent [5] wrote that "By considering limiting cases in this way, the design of the beams and the columns could largely be divorced". Although the papers propose a possible approach to design, it is not developed into a complete method. Experimental work by Davison et al. [7,8] and Gibbons et al. [9,10] on full size semi-rigidly connected braced steel frames demonstrated this same phenomenon and formed the basis of a design method which assumed the columns to be pin ended and ignored the column moments because at the ultimate limit state the beneficial restraining effect of the attached beams outweighed the detrimental effect of the diminishing moments as the column buckles [11,12].

1.2. Design using plastic rotations (moment shedding)

A new design method for discontinuous columns in braced frames was proposed by King [13] using moment shedding so that the columns are designed for zero end-moment even if the connection of the columns to the beams is effectively rigid. The proposed method is for square hollow section columns, assuming that the full cross-section is effective. The columns are assumed to derive no stability from the

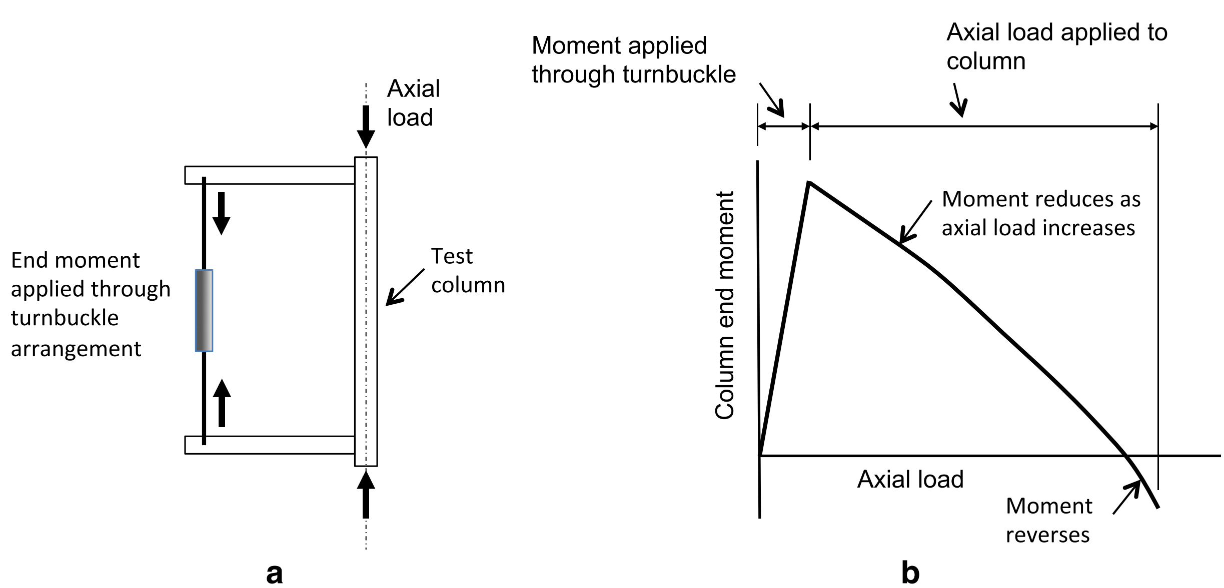

Fig. 2. Gent & Milner (a) Experimental arrangement (b) Moment shedding from increasing axial load.