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Inelastic restrained distortional buckling of continuous composite T-beams

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ABSTRACT

This paper develops a method of inelastic buckling analysis of thin-walled sections to study buckling characteristics of single span and two-span composite T-section beams in the inelastic range of structural response. The method is based on a bubble-augmented spline finite strip method, developed elsewhere by the authors, and confirmed as both accurate and efficient for the elastic buckling analysis of thin-walled structural members and plates. The method admits both flexural and membrane buckling deformations and it allows for consideration of structures with intermediate supports and a variety of boundary conditions that may be prescribed at the ends of plate assembly. The analysis includes the so-called Tendon Force Concept developed at Cambridge University for residual stresses caused by the process of fabrication, and the non-linear stress–strain properties of the structural steel from which the joist section is made. The inelastic restrained distortional buckling (RDB) of continuous composite T-section beams under transverse loading and moment gradient is investigated, and conclusions are drawn that address the influence of geometry, residual stresses, member length, the rigid restraint provided by the concrete and the degree of reinforcement in the concrete element.

1. Introduction

Composite steel–concrete beam construction takes advantage of the best qualities of each of its constituent materials: the high compressive strength of the concrete, its mass, stiffness and fire resistance and the high tensile capacity of the steel and its ductility. This ideal marriage of the two materials is to some extent violated in composite steel–concrete beams continuous over one or more supports. Unlike simply supported beams, continuous beams when loaded by gravity loads are subjected to positive sagging moments in the regions between the supports and to negative hogging moments at the internal supports, or between the points of contraflexure (Fig. 1). Notwithstanding many advantages of a continuous composite beam construction over a simply supported composite beam, i.e. a higher span to depth ratio, reduced deflections, favourable moment redistribution and a higher fundamental frequency of vibration due to its higher stiffness, the buckling characteristics of such structural configurations in the negative-moment regions are far more complex and far less understood than those of simply supported composite beams and reasonably well-researched continuous plain steel I-beams.

Buckling in continuous composite steel–concrete beams is somewhat unique, in that under negative bending the slab restrains the tension region of the steel and the neutral axis is not located at the mid-height of the web but is shifted towards the top flange, and the steel part is therefore subjected mainly to compressive strains. The difficulty with the negative bending condition in a composite beam is that the buckling mode of the steel beam is one of restrained distortional buckling (RDB), in which the top flange is fully restrained by the concrete slab and the bottom flange is restrained by the flexibility of the web only, as shown in Fig. 2. Distortional buckling of unrestrained beams of practical configuration usually takes place at a load that is not significantly less than that for lateral buckling. RDB,

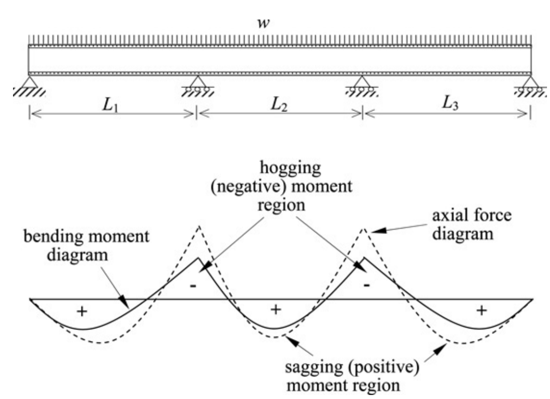

Fig. 1. Three span continuous composite beam; bending moment and axial force distribution in the steel joist.

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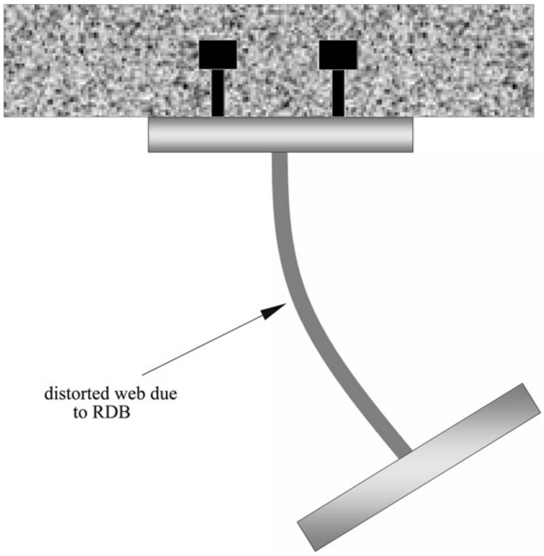

Fig. 2. Composite beam cross section with restrained distortional buckling (RDB).

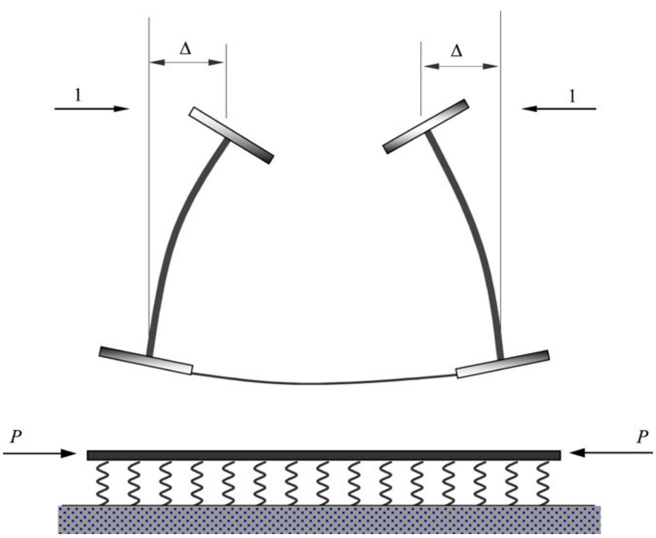

Fig. 3. U-frame model.

however, is fundamentally different to the more commonly studied distortional buckling of laterally unrestrained beams and can have a profound influence on the buckling behaviour of beams with continuous restraint at the level of the tension flange [1,2].

The RDB behaviour of continuous composite beams is usually approximated conservatively in design codes as being of a lateral–torsional type. However, studies of buckling in composite I-section bridge girders without intermediate stiffeners [3] concluded that the design ultimate buckling loads could be more than doubled in many instances, when the buckling was considered as RDB rather than lateral–torsional. The most common model for considering RDB in design is the inverted U-frame method [4], in which the top compression flange of the I-section is considered as a strut compressed uniformly along its length by the maximum bending stress that is induced in it, and which is restrained by a continuous Winkler spring whose stiffness is that of the web in the plane of its cross-section acting as a cantilever, as illustrated in Fig. 3. In reality, continuous composite beams are generally used in situations in which there is considerable moment gradient, and so the U-frame approach tends to be conservative, excessively so in most cases. The current design guidance available in national and international codes of practice is rather limited and, as evident from existing literature, overly conservative.

The interaction between plastic behaviour and instability is important for steel I-sections with stocky flanges, or for plate girders where the residual stresses represent a significant factor in their design. In such structural configurations, sections may buckle inelastically at a moment which is lower than the elastic buckling moment. It is also well recognised that the ductility of composite beams in negative bending is influenced by considerations of the stability of the structural steel. For plastic design, it is important to ensure that attainment of a plastic mechanism with its associated redistribution of bending moment will precede inelastic distortional buckling. The transition from elastic to plastic behaviour in a continuous composite beam under increasing load involves redistribution of longitudinal bending moments, to an extent that is greater in a composite beam than in a steel beam. The method reported by Nethercot and Trahair [5] established a relationship between the plastic moment at which inelastic buckling will occur and the elastic buckling moment, and this study formed the basis of the lateral buckling design strength curves in a number of national steel standards. However, it appears that the relationship between the full plastic moment and the elastic buckling moment at which lateral buckling occurs is different from that at which distortional buckling occurs [6], especially if the beam has a continuous restraint.

Tests conducted on continuous composite beams and on simply supported beams in negative bending [7–11] have verified that the modes of buckling may be classified as local and/or restrained distortional buckling (RDB). In all these tests, a complex interaction between local and distortional buckling that takes place at or near the maximum load was observed. The results showed that interaction between local and lateral–distortional buckling governs the ultimate strength of the test specimens and is strongly influenced by initial imperfections. Experimental studies of distortional buckling of composite beams are very rare and even elastic distortional buckling experiments on I-section beams have received very little treatment [12] in comparison to other section profiles [13].

There is both theoretical and experimental evidence [3] that in uniform composite bridge members, local buckling of the bottom flange at the face of an internal support will always precede RDB. This suggests that the design criterion for such a region with a compact flange could be nominal first yield of the steel, instead of the lower stress (determined by an inappropriate treatment of lateral buckling) which at present governs the design of most unbraced continuous beams. If this criterion was adopted, plasticity would occur earlier than assumed in design, due to the large residual stresses that can occur, particularly in the flanges of welded plate girders.

Plastic design of continuous composite beams has many advantages; however this can only be achieved if buckling is prevented. It is also well recognised that the ability of construction materials to deform plastically is economically beneficial, and allows high stress peaks to be levelled out the first time that the load to form a plastic hinge is reached. Design procedures based on plasticity have been adopted in most limit states steel structures codes, such as the Eurocode 3 [14] and the Australian Standard AS4100 [15].

Inelastic local buckling of plate assemblies has been investigated by a number of researchers. Gradzki and Kowal-Michalska [16] used deformation theory to study the inelastic local buckling behaviour of thin-walled columns. Dawe and Kulak [17] and Bradford [18] used the material property moduli derived from flow theory and Lay's [19] expression for the effective shear modulus to study the inelastic local buckling behaviour of I-sections and composite beams. Plank [20] modified the finite strip method