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Validation of a general design procedure for the transverse impact capacity of steel columns

M.R. Bambach *

School of Civil Engineering, The University of Sydney, NSW 2006, Australia

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ABSTRACT

There has been considerable interest over the past decade in the transverse impact response of steel columns and composite steel-concrete columns. While several researchers have developed analytical procedures for specific types of steel sections, a unified design approach has yet to be established. The present paper develops a generalised rigid-plastic procedure to calculate the design transverse impact capacity for a wide range of steel and composite column sections. The design procedure is specifically developed to align with current international hot-rolled steel design specifications, including those in Australia, North America, the European Union and China. A database of 320 impact experiments is collated from the literature, and used to validate the general design procedure. It is demonstrated that the procedure provides robust transverse impact capacity predictions for solid rectangular steel sections, steel I-sections, circular and rectangular steel hollow sections, concrete filled circular and rectangular steel hollow sections and concrete filled double skin steel hollow sections. In some cases stainless steel members were additionally included.

1. Introduction

The transverse impact response of steel compression members is of interest to a broad range of disciplines, including: transportation structures (e.g. overpass columns and bridge piers); mining structures (e.g. conveyor columns and general infrastructure); offshore structures (e.g. tower, jacket and riser members); critical infrastructure; and safety, protective or security structures. There is a long history of research into the behaviour of metal members under transverse impacts dating from the 1970s, including; generic studies of the underlying mechanics of solid metal members [1–14], investigations of steel circular hollow sections typical to the piping industry [15–25], and steel tubular sections typical to the offshore structures industry [26–37]. More recently, there has been substantial interest in the transverse impact of steel hollow section compression members used as columns in infrastructure, wherein concrete filling is often employed and other metals such as stainless steel are increasingly used [38–46].

While many of these studies have developed analytical procedures to describe the mechanical behaviour of solid metal [6–9,11,12] and hollow sections [19–21,29,30,32,37], these have typically been developed from a mechanical standpoint and do not lend themselves to being directly adapted for routine civil-structural design of columns. Additionally, much of the early theoretical work was directed towards the piping and offshore structure applications, wherein the response was dominated by local deformations (denting) with little or no overall (member) deformations [25,27,31–34]. Local and overall deformations of circular hollow sections are illustrated in Fig. 1. In the application of such sections as columns in infrastructure or other structural applications, overall deformations are of primary concern, especially in applications where the sections are concrete filled and cannot undergo substantive local deformations.

Some recent studies of structural columns subjected to transverse impact have developed analytical tools to describe the behaviour, particularly with respect to the transverse member deformation [41,45,46]. For example, the author previously developed explicit procedures based on plastic collapse mechanism theory [45,46], however these were only validated against the authors own experiments on hollow and concrete filled steel and stainless steel rectangular hollow sections. No studies have yet to address the development of generalised design procedures for steel columns for incorporation into international structural steel specifications. While quasi-static plastic design procedures are provided in all major hot-rolled steel specifications (Australia, North America, the European Union and China), their applicability to general column transverse impact design have yet to be established. The aim of the present study is to provide an explicit and generalised design approach to assess the transverse impact capacity of steel compression members, based on rigid-plastic analysis, and to validate the procedures against a broad range of experimental data.

* Corresponding author.
E-mail address: mike.bambach@sydney.edu.au.

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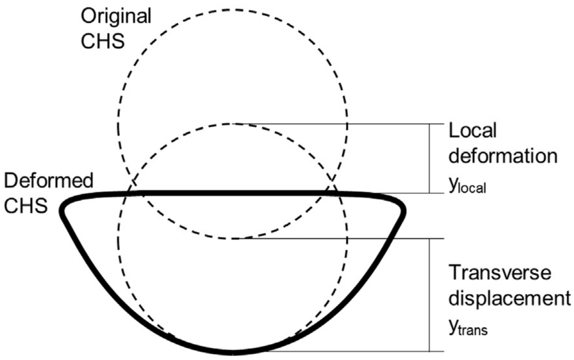


Fig. 1. Local deformation and overall transverse displacement of a steel circular hollow section.

2. Rigid-plastic theorem for transverse force resistance

Routine plastic collapse analysis may be used to explicitly furnish the rigid-plastic solution for the bending response of a structural member subjected to a force transverse to the member length. The procedure follows from an assessment of the boundary conditions, wherein rotational restraint at the member ends will require the formation of plastic hinges, and a plastic hinge will additionally form at the point of load application. The principle of virtual work may be used to furnish the classical solution for the plastic collapse load associated with the bending resistance of the plastic hinges. The corresponding energy dissipated in plastic bending (work), may be solved simply by multiplying the plastic load by the transverse plastic displacement (y_{trans}), some common examples of which are shown in Fig. 2.

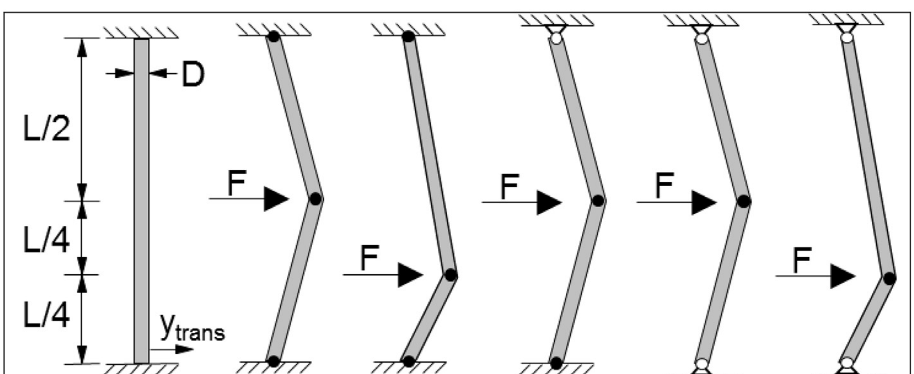
If the member is axially restrained, axial tension membrane forces will develop in addition to the plastic bending resistance, which further increases the transverse force resistance. This is a second order effect that results from the development of finite transverse displacement. The combined bending and axial tension membrane force resistance may be solved explicitly from the kinematic, constitutive material and equilibrium relations [4,6,7,9,45], some common examples of which are shown in Fig. 2. The total transverse force resistance may be expressed as the sum of the bending and axial tension membrane resistances, as exemplified in Fig. 3 and Eq. 1 for a member of length L with rotational and axial restraint at both ends. The total resistance is therefore a function of; the transverse displacement (y_{trans}), the section plastic moment (M_p) and the plastic axial force (i.e. the yield force in tension, N_{yt}), calculated by traditional methods. The coefficients in the relation result directly from; the member boundary conditions of rotational restraint and axial restraint, and the exact location of the transverse force (Fig. 2).

$$F = \frac{8M_p}{L} + \frac{{N_{yt}}^2 {y_{trans}}^2}{2M_p L} \tag{1}$$

As is evident from Eq. (1) and Fig. 3, initially when the plastic collapse mechanism develops, the force resistance is due to the bending resistance of the plastic hinges only. However, with axial restraint, as finite transverse displacement develops the axial tension membrane resistance becomes increasingly important to the total resistance (particularly after y_{trans}/D exceeds one). In accordance with rigid-plastic theory, the initial elastic portion of the response is neglected. Having established the transverse force resistance function with respect to the transverse displacement, the explicit solution for the corresponding energy dissipated in the process is furnished simply by integrating the force function between zero and some magnitude of transverse displacement, as exemplified in Eq. (2) for a member with rotational and axial restraint at both ends (other common boundary conditions are shown in Fig. 2).

$$E = \int_0^{y_{trans}} F.dy = \frac{8M_p y_{trans}}{L} + \frac{{N_{yt}}^2 {y_{trans}}^3}{6M_p L} \tag{2}$$

Importantly, since the foregoing analysis is strictly in accordance with established plastic analysis and equilibrium theorems, from a design standpoint the analysis may be simply referred to as "design by plastic analysis". It has long been established that metal members undergoing low velocity impacts will follow the quasi-static plastic response closely, albeit with some strain-rate and inertia effects in certain circumstances. Accordingly, the "design by plastic analysis" procedure is nominally applicable to members subjected to transverse impact loads, as will be demonstrated in the proceeding sections.



Bending energy:	$\frac{8M_p}{L} y_{trans}$	$\frac{10.7M_p}{L} y_{trans}$	$\frac{6M_p}{L} y_{trans}$	$\frac{4M_p}{L} y_{trans}$	$\frac{5.3M_p}{L} y_{trans}$
Axial tension energy: (if axially restrained)	$\frac{{N_{yt}}^2 {y_{trans}}^3}{6M_p L}$	$\frac{{N_{yt}}^2 {y_{trans}}^3}{6M_p L}$	$\frac{{N_{yt}}^2 {y_{trans}}^3}{4.5M_p L}$	$\frac{{N_{yt}}^2 {y_{trans}}^3}{3M_p L}$	$\frac{{N_{yt}}^2 {y_{trans}}^3}{3M_p L}$

Fig. 2. Plastic collapse mechanisms investigated experimentally and the associated energy dissipation (the bending energy, or the sum of the bending energy and the axial tension energy if axially restrained) (black circle = plastic hinge, hollow circle = regular hinge).