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Behaviour and design of steel members with web openings under combined bending, shear and compression

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ABSTRACT

This paper examines the behaviour of steel beams with web openings under combined axial compression, bending moment and shear force through numerical simulation modelling. The numerical simulation results show that under either pure compression or pure bending, the plastic axial or bending capacities of beams are limited by buckling of the compressive tee-section with the reduction being much more significant in the case of axial compression. The numerical study results also show that when dealing with the general situation of a beam under combined axial compression, bending moment and shear force, the effect of compressive force and consequent tee-section buckling should be included to reduce both the bending moment and shear resistances of the perforated section.

Based on the numerical simulation results, an analytical method has been derived. The method was developed by modifying existing shear-moment interaction equations for the Vierendeel mechanism to incorporate the influences of tee-section buckling and additional compressive force in reducing the bending moment and shear capacities.

To account for the effects of additional compression force on bending resistance, the plastic moment-axial compression interaction equation may be used, however, the plastic bending moment capacity (without axial compression) and the plastic compression resistance (without bending) should be replaced by those under the influence of T-section buckling. To allow for T-section buckling, an effective T-section buckling length of 0.5L or L (where L is the T-section length) should be used when calculating the bending moment or compression resistance of the perforated section. The shear resistance of the perforated section is obtained by calculating a critical shear stress in the T-section. This critical shear stress -direct stress interaction is according to the von Mises equation, but the square power in the von Mises equation is replaced by a function that reflects the influence of T-section buckling.

A comparison between the numerical simulation results and the analytical results using the proposed method indicates very good agreement, with the inaccuracy mainly attributed to inaccurate calculation of the bending – shear interaction of the existing methods which do not consider the effects of additional compression and T-section buckling.

1. Introduction

Steel sections with web openings are frequently used in construction owing to their many advantages such as attractive architectural appearance when used as façade support (Fig. 1a) and flexibility in accommodating building services when used as floor beams (Fig. 1b).

Fig. 2 shows a section with opening (rectangle, circle or elongated circle) with symbols for dimensions. Circular and elongated openings may be treated as equivalent rectangular openings of dimensions (l_o' and d_o') as shown in the figure. In this paper, it is assumed that the beam cross-section and the openings are symmetrical about the centre line.

Research on steel beams with web openings dates back many decades starting with early experimental investigations on castellated beams [2,3,4] and tests on beams with isolated circular or rectangular openings such as [5,6,7,8,9] attempting to understand the deflection behaviour of such beams and to obtain the stresses around the openings. Throughout the years, with more advanced finite element studies on beams with different quantity, shape and size of openings [10,11,12,13], research on this subject has matured leading to practical design methods.

One important shortcoming of these research studies and design methods is that the steel member is subject to lateral load only resulting in bending and shear. However, steel members with web openings may be subjected to combined axial compression, bending and shear, as in façade support structures.

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Notations

A	cross-section area of I-section
A_o	cross-section area of perforated I-section
$A_{o,w}$	cross-section area of perforated web between flanges
A_t	cross-section area of tee-section
B_f	width of flange
d	depth between flanges of an I-section
d_c	distance between centroids of top and bottom tee-sections
d_{Nf}	height of flange thickness subjected to axial compressive force
d_o	depth of opening
d_o'	depth of equivalent rectangular opening for a circular opening
$d_{o,w,N}$	height of perforated web subjected to axial compressive force
d_t	depth of tee-section
d_{wt}	depth of web of tee-section
E	modulus of elasticity
f_{crit}	critical buckling stress of section with opening
f_n	average direct stress over cross-section
f_u	ultimate strength
$f_{u,f}$	ultimate strength of flange
$f_{u,w}$	ultimate strength of web
f_v	shear strength
f_{vn}	reduced shear strength due to axial compressive force
f_y	yield strength
$f_{y,f}$	yield strength of flange
$f_{y,w}$	yield strength of web
h	overall height of I-section
I_t	second moment of area of tee-section
l	span of beam
l_o	length of opening
l_o'	length of equivalent rectangular opening for circular and elongated circle openings
$l_{t,cr}$	critical length of tee-section
M_{Abaqus}	failure bending moment in ABAQUS
$M_{o,b}$	bending moment capacity of section with opening reduced for tee-section buckling
$M_{o,b,N}$	buckling moment capacity of section with opening reduced for axial compressive force
$M_{o,pl}$	plastic bending moment capacity of a perforated I-section
$M_{o,pl,vi}$	plastic moment capacity of section with opening reduced for Vierendeel mechanism
$M_{o,sd}$	applied bending moment at the centreline of an opening
M_{pl}	plastic bending moment capacity of solid I-section
M_{sd}	applied bending moment
$M_{t,,pl}$	Plastic moment capacity of tee-section
$M_{t,,sd}$	Vierendeel moments at opening corners on tee-sections
$M_{vi,sd}$	total Vierendeel moment over opening due to transfer of shear
N_{Abaqus}	axial failure load in ABAQUS
$N_{o,b}$	axial compressive resistance of section with opening
$N_{o,pl}$	plastic axial capacity of perforated I-section
$N_{o,w,pl}$	plastic axial capacity of perforated web
N_{pl}	plastic axial capacity of solid I-section
N_{sd}	applied axial force
$N_{t,b}$	axial bucking resistance of tee-section
$N_{t,cr}$	critical elastic Euler buckling load of tee-section
$N_{t,pl}$	plastic axial capacity of tee-section
$N_{t,sd}$	applied axial force on tee-sections
P.N.A	plastic neutral axis
t_f	thickness of flange
t_w	thickness of web
UDL	uniformly distributed load
$V_{o,pl}$	plastic shear capacity of a perforated I-section
$V_{o,pl,N}$	plastic shear capacity of a perforated I-section reduced for axial compressive force
$V_{o,pl,vi}$	plastic shear capacity of a perforated I-section reduced for Vierendeel mechanism
$V_{o,sd}$	applied shear force at the centreline of an opening
$V_{t,sd}$	applied shear force on tee-section
$W_{o,pl}$	plastic section modulus of perforated I-section
W_{pl}	plastic section modulus of I-section
w	uniformly distributed load
x_o	distance of opening centreline from support
α	imperfection factor
$\bar{\lambda}_t$.	non-dimensional slenderness of tee-section
ρ	axial load ratio
τ	shear stress
σ	direct stress
$\bar{\upsilon}$	coupled shear capacity ratio
χ_t	reduction factor for buckling of tee-section

Fig. 3 shows the global and local forces in a steel member with web openings under lateral load generating bending moments and shear forces. Under such loading conditions, the opening may fail by either bending, shear, Vierendeel mechanism or tee-section buckling.

The behaviour and design for bending and shear resistances of beams with web openings is the same as for solid beams, the only difference being that the section properties of the perforated section (solid section minus the removed part of the web) are used. They will not be considered any further in this paper.

This paper will deal with Vierendeel mechanism, shown in Fig. 4, which is the most critical failure mode of openings. In this mechanism, transfer of a shear force across the opening leads to the generation of secondary bending moments and formation of plastic hinges in the tee-sections near the opening corners [14,11,15,16]. This paper will investigate how an additional axial compression affects the Vierendeel mechanism.

Despite numerous available design proposals for Vierendeel mechanism, they can be all categorised into two main groups. They either consider the tee-section resistance at the four corners of an opening or the perforated I-section capacity at the centreline of the opening. In the tee-section method, such as those given by [1,18,19,20,21], the moment resistances of the four tee-sections at the corners of the opening are reduced for the co-existing axial loads generated by the applied global moment. In the perforated section method [22,23,16], the resistance of the beam depends on the section resistance of the perforated section under combined global shear and bending moment applied at the centreline of the opening. The influence of Vierendeel moments is taken into account by reducing the basic shear capacity due to Vierendeel moments.

The SCI publication P355 [1], which is commonly used to design steel beams with openings, uses the tee-section method. The design check for Vierendeel moment capacity of the section with opening is:

$$M_{o,pl,vi} = 4M_{t,pl}\left[1-\left(\frac{N_{t,sd}}{N_{t,pl}}\right)^2\right] \tag{1}$$

This resistance should not be exceeded by the total applied Vierendeel moment caused by the transfer of shear force across the opening calculated below:

$$M_{vi,sd} = V_{o,sd}l_o \tag{2}$$

However, Chung and co-workers [24,25,12,10] found the above method conservative because it ignores load redistribution within the