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Application of corrugated plates as the web of steel coupling beams

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ABSTRACT

Nowadays, steel coupling beams are used as an efficient alternative to reinforced concrete (RC) coupling beams. Particularly in the coupled shear walls system, coupling beams are the main members for dissipating seismic energy. In this paper, for the first time the application of corrugated plates as the web of steel coupling beams (rather than flat web and its stiffeners) is studied as a proposition for improving seismic behavior of such beams. The study addresses the linear elastic buckling analysis and non-linear analysis of steel coupling beams with flat and corrugated webs using finite element technique for which ANSYS software is employed. 160 models have been studied, considering parameters such as shape of web plate (flat and three corrugated types, including trapezoidal, curved, and zigzag), web thickness, number of corrugations, and corrugation angle. The finite element results are validated through comparison with the experimental results of a common steel coupling beam, tested by other researchers. In addition to the advantages of eliminating web stiffeners, results of this study show that the application of corrugated web with the proposed geometric criteria makes it possible to achieve further rotation capacity in comparison with common steel coupling beams. Finally, a design approach for corrugated web of steel coupling beams, accompanied by a practical example, is presented.

1. Introduction

Coupled shear walls system is considered as one of the most efficient seismic load resisting systems in mid to high-rise buildings. When the strength of coupling beams is distributed appropriately over the height of a building, desirable hinge formation occurs in the beams prior to hinge formation at the base of the wall piers [1]. Steel coupling beams are viable alternatives to reinforced concrete (RC) beams, particularly when height restrictions do not permit use of deep RC beams or when the required capacity, stiffness, or deformation demands cannot be met economically by RC beams. The behavior of coupling beams is similar to link beams in eccentrically braced frames [2]. Based on previous researches, shear-critical steel coupling beams have remarkable energy absorption capacity, significant ductility, and energy dissipation characteristics when subjected to cyclic loadings [3]. Furthermore, certainty of plastic hinge formation in the beams as the limit state governing behavior is significantly greater relative to the more common RC coupling beams (diagonally reinforced concrete beams). Fewer construction difficulties of steel coupling beams in comparison with RC coupling beams (construction difficulties related to placing diagonal and transverse reinforcements) is the other significant advantage of such beams. The general design philosophy of using steel coupling beams to achieve maximum ductility is to ensure that the flanges of the beam remain elastic while the web yields in shear. Also appropriate slenderness ratios of the flanges and web should be considered in order to preclude local flange or web buckling. To delay web crippling and buckling, the use of transverse stiffeners is inevitable. However, actions resulting from stiffeners warping (as a result of beam deformation) over areas with high residual stresses around flange, web, and stiffener connection zone lead to an increase in probability of premature web rupture before its buckling. Consequently, beam rotation capacity decreases considerably [4,5].

In recent years, the use of corrugated plates as the web of girders in bridges and single-story steel buildings has been increased. Considering significant out-of-plane stiffness of corrugated plates, such plates have much higher buckling strength in compared with flat plates; thus by using them as the beam web, the necessity of using stiffeners is eliminated as well as reducing the required web thickness.

Considering negligible axial stiffness of corrugated web in longitudinal direction of these beams (known as accordion effect), flexural strength of such beams is completely provided by flanges (without contribution of beam web) and shear strength is provided by the web; therefore there is no interaction between shear and flexural behaviors. For the first time, Easley and McFarland [6] studied buckling behavior of the corrugated plates and developed an equation to calculate global buckling stress, assuming corrugated plate as an orthotropic flat plate. Recently extensive studies have been conducted on behavior

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Notation

A_w	required web area
a	flat (or horizontal) sub-panels width
b	horizontal projection of inclined sub-panels width
b_f	flange width
c	inclined sub-panel width
D	maximum out-of-plane deformation of the web resulted from eigenvalue buckling analysis
D_x	bending stiffness of corrugated plate about axis x
D_y	bending stiffness of corrugated plate about axis y
d	corrugation depth
d_s	section height
E	Young's modulus
f_y	yield stress of steel
f_{yf}	yield stress of flange steel
f_{yw}	yield stress of web steel
h_w	web height
K_L	local shear buckling coefficient
L_{clear}	clear span of coupling beam
L_e	embedment length of steel coupling beam into shear walls
$L_{eff.}$	effective length of steel coupling beam
M_s	bending moment corresponding to plastic shear strength
M_u	bending moment capacity
N	number of corrugations (or number of half-waves)
n	order of Eq. (10)
R	radius of corrugation curve (in curved corrugated models)
SD	standard deviation
SF	scale factor
t_f	flange thickness
t_s	stiffener thickness
t_w (or t)	web thickness
U	Eurocode suggestion for out-of-plane imperfection of plates;
V_n	nominal shear strength
V_p	plastic design shear strength
V_u	ultimate shear strength
V_y	yield shear strength
V_u/V_y	dimensionless shear strength (or over-strength factor)
w	maximum fold width, max. (a, b)
$Z_{req.}$	required plastic section modulus
β	global buckling coefficient
η	length reduction factor
λ_s	shear buckling parameter (or slenderness parameter)
$\lambda_{s,\ eq.}$	shear buckling parameter from equations
$\lambda_{s,\ FEM}$	shear buckling parameter from FE
$\lambda_{s,\ req.}$	required shear buckling parameter
θ	corrugation angle
θ_u	ultimate rotation
τ_{cr}	shear buckling strength
τ_y	shear yielding strength of steel web
τ_{cr}^e	elastic shear buckling strength
$\tau_{cr,L}^e$	elastic local shear buckling strength of corrugated sub-panel
$\tau_{cr,G}^e$	elastic global shear buckling strength
v	Poisson's ratio
φ_v	reduction factor of shear strength
φ_b	reduction factor of flexural strength

of beams with corrugated web subjected to gravity loads; however, the behavior of such beams as a seismic energy absorbing element e.g. steel coupling beams has not been studied yet [7–14].

This research investigates the use of corrugated plate instead of flat web with stiffeners as a means of improving seismic behavior of steel coupling beams. In this respect, finite element method (FEM) was selected as a useful and powerful tool in engineering sciences and ANSYS software was employed for modeling purposes [15]. The validation of finite element results is obtained through comparison with the experimental results of a common steel coupling beam, tested by Park and Yun [7]. Considering parameters such as shape of web plate (flat and three corrugated types including trapezoidal, curved, and zigzag), web thickness, number of corrugations, and corrugation angle, 160 models are analyzed.

In the first step, shear buckling parameter (or slenderness parameter, the ratio of the effective length of a member to the least radius of gyration of its cross section) of corrugated web, λ_s, is calculated by linear elastic buckling analysis. Then, to determine appropriate equations for calculation of λ_s (in corrugated plates with the geometry of steel coupling beams web), the λ_s values obtained from finite element analysis (FEA) are compared to the ones obtained from proposed equations by other researchers. Afterwards, ultimate rotation (θ_u) of the finite element (FE) models is determined by conducting nonlinear analysis and finally, fitted trend lines to the points of ($\theta_u - \lambda_s$) are presented. Accordingly, using the curves, it is possible to determine the required λ_s to achieve target rotation. By making appropriate assumptions of corrugation angle and number of half-waves for the selected type of corrugation, corresponding λ_s calculated by proposed equations must be less than or equal to the one determined by the fitted curves. In the end, a design approach for corrugated web of steel coupling beams accompanied by a practical example is presented.

2. Concepts and equations

Due to the need of concepts and design equations of steel coupling beams and corrugated web beams in this paper, this section presents concepts and required equations of the beams.

2.1. Steel coupling beams with flat web

The steel coupling beam can be designed in accordance with the seismic design requirements for link beams in eccentrically braced frame of AISC steel design standard [16].

Step 1: calculation of the required area of the web, A_w, to resist ultimate shear strength, V_u, by Eq. (1).

$$V_u \le \varphi_v V_n = 0.6\varphi_v f_{yw} A_w = 0.6\varphi_v f_{yw}\left(d_s - 2t_f\right)t_w \tag{1}$$

where, V_n is nominal shear strength, φ_v is reduction factor of shear strength, f_{yw} is yield stress of web steel, d_s is section height, and t_f and t_w are flanges and web thicknesses, respectively.

Step 2: calculation of the required plastic section modulus, $Z_{req.}$ as the section can resist bending moment M_s which is corresponding to plastic design shear strength, V_p. Values $Z_{req.}$ and M_s are calculated by Eqs. (2) and (3), respectively. Also, in this step strain hardening should be considered.

$$Z_{req.} \ge {}^{M_s}\Big/_{\varphi_b f_y} \tag{2}$$

$$M_s = \frac{L_{eff}}{1.6} \times V_p = \frac{(L_{clear} + 2l_e/5)}{1.6} \times 1.35 V_n \tag{3}$$

where, f_y is yield stress of steel and φ_b is reduction factor of flexural strength. Also, $L_{eff.}$ and L_{clear} are the effective length and the clear