PLASTIC BEHAVIOUR OF STRENGTHENED COLD-FORMED STEEL SECTION

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To my God, Allah *'azza wa jalla*

Then to my beloved parents, parents in law, wife and children

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ABSTRACT

To date, the use of cold-formed steel on single storey industrial buildings particularly as structural element of a portal frame is restricted. Mostly, its application is as roof and wall framing, cladding, purlins and rails. Compared with hot-rolled steel, the use of cold-formed steel on a building has advantages such as light self-weight and corrosion-free problems, even though these are weaknesses to be overcome. The main problems are local buckling and low connection capacity. From the previous study, it was shown that cod-formed rectangular hollow portal frame using thick section indicated the plastic behaviour. This section is uneasy to be derived at site. Besides, some connection methods have also been suggested by previous researchers using bolts, rivets, press and weld but such the connections cannot reach rigid connection as needed for plastic design of portal frame. This research intends to study strengthening methods of cold-formed steel section and the connection performance improvement using cover plate. From this study, it is expected that cold-formed steel section can achieve plastic section and the rigid connection can be reached. The study was performed in two stages. In the first stage, the study on small cold-formed steel beams was done, while in the second stage, the study investigated a full scale of cold-formed steel beams and the connections. Specimens of this research consist of strengthened cold-formed closed beams and the moment connections. The beams are strengthened using a splice of hot rolled plate attached to the original section by screws and weld. The beams are in various design strength, thickness, screw spacing and number of web screw rows. Three types of connection i.e. welded, unbraced cover and braced cover connections were constructed for the specimens. Self-drilling screws for the section strengthening were applied on the connected members outside the cover plate. The experimental results were compared to the theoretical one. From this study, it can be concluded that the applied strengthening method significantly increase the moment capacity of the cold-formed steel sections. Similarly, the braced cover connection improves the connection to be rigid connection.

ABSTRAK

Sehingga kini, penggunaan keluli terbentuk sejuk pada binaan-binaan perindustrian satu tingkat khasnya sebagai elemen struktur kerangka portal belum banyak dibuat. Penggunaannya pada binaan majoriti digunakan sebagai kekuda, kerangka bumbung, dinding dan bahagian-bahagian penyokong binaan lain. Dibandingkan dengan keluli tergelek panas, penggunaan keluli terbentuk sejuk pada struktur binaan mempunyai kelebihan-kelebihan antara lain berat diri kecil dan tak ada soalan kakisan, namun ada kelemahan yang perlu dibaiki agar boleh digunakan secara lebih luas lagi. Permasalahan utama yang menghalang adalah terjadinya lengkokan tempatan dan keupayaan sambungannya yang rendah. Penyelidik sebelumnya menyatakan bahawa kerangka portal yang mengggunakan keratan segiempat tepat geronggang yang tebal dapat menunjukkan kelakuan plastik. Keratan seperti ini tidak mudah diperolehi di lapangan. Disamping itu pelbagai kaedah penyambungan yang dicadangkan penyelidik sebelumnya dengan mengunakan bolt, rivet, tekanan mahupun kimpal, bagaimanapun tidak boleh berkelakuan sebagai sambungan tegar seperti yang diperlukan pada reka bentuk plastik kerangka portal. Penyelidikan ini bermaksud menyiasat perkuatan keratan keluli terbentuk sejuk dengan cara menambah ketebalan elemen-elemen keratan yang tertekan serta meningkatkan keupayaan sambungannya dengan penambahan plat penutup. Dari hasil kajian ini diharapkan keratan-keratan keluli terbentuk sejuk dapat mencapai kategori keratan plastik serta sambungan tegar anggota-anggota keluli terbentuk sejuk dapat dicapai. Penyelidikan ini dilakukan dua tahap iaitu kajian berskala pada rasuk-rasuk keluli terbentuk sejuk dan penyelidikan dengan spesimen skala penuh rasuk-rasuk keluli terbentuk sejuk yang diperkuat serta sambungan momennya. Keratan rasuk diperkuat dengan menambah keluli tergelek panas yang dikimpal dan diperkuatkan dengan skru gerudi-diri dengan pengaturan yang berbeza. Tiga jenis sambungan iaitu sambungan kimpal, sambungan penutup tanpa penguat dan sambungan penutup dengan penguat dibuat sebagai spesimen. Skru gerudi-diri dipasang pada batang-batang sambungan diluar kawasan plat penutup. Hasil penyelidikan tersebut kemudian dibanding dengan hasil pengiraan teori. Dari penyelidikan ini dapat disimpulkan bahawa kaedah perkuatan yang dilakukan dapat meningkatkan keupayaan keratan keluli terbentuk sejuk secara nyata meskipun belum mencapai keratan plastik. Begitu juga dengan kaedah penyambungan yang dicadangkan dapat menambah ketegaran sambungan sehingga mencapai kriteria sambungan tegar.

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LIST OF SYMBOLS

A	-	section area
b	-	flange or section width; haunch length; flat width of the compression element
b_p	-	internal width of web plate
b_o	-	outstand of plate width
b_1	-	stiff bearing length
B	-	overall section width; constant of elastic analysis of portal frame; flange width for unstiffened or edge stiffened flanges, or half the overall flange width for stiffened flanges
B_b	-	beam flange width
B_c	-	column flange width
B_1	-	section width
B_2	-	section depth
B_{eff}	-	effective section width
c	-	distance from the end of the beam to the load or the reaction
C	-	constant of elastic analysis of portal frame; compression force
C_b	-	coefficient which may be conservatively assumed to be unity
C_{exp}	-	experimental compression force
C_{th}	-	theoretical compression force
C_3	-	constant
C_4	-	constant
C_{12}	-	constant
d	-	section or web depth; haunch depth; deflection at mid-span
D	-	overall section depth; overall web depth
D_e	-	equivalent depth of an intermediately stiffened web
D_2	-	distance between the centre line of the intermediate stiffener web and the tension element

e	-	height to hinge location at the bottom of haunch
E	-	modulus of elasticity
E_s	-	modulus of elasticity of steel
E_g	-	modulus of elasticity of gypsum board
f	-	rise of portal frame roof
f_a	-	average stress
f_{av}	-	average shear stress
f_v	-	shear stress
f_c	-	compressive stress of effective element
F_v	-	shear force
$F_{v\ exp}$	-	experimental shear force
$F_{v\ th}$	-	theoretical shear force
F_w	-	concentrated web load or reaction
g	-	roof height from base
G	-	shear modulus
h	-	eaves height of portal frame; constant which is equal to B_2/B_1
H	-	horizontal force at base
H_e	-	elastic horizontal force at base
H_p	-	plastic horizontal force at base
I_{app}	-	approach moment of inertia
I_g	-	moment of inertia of gypsum board section
I_s	-	moment of inertia of steel section
I_{th}	-	theoretical moment of inertia
I_x	-	moment of inertia
I_{xr}	-	moment of inertia of reduced section
I_{xx}	-	moment of inertia referring to X axis
I_1	-	moment of inertia of column
I_2	-	moment of inertia of rafter
k	-	constant of elastic analysis of portal frame; constant which is equal to $p_y / 228$
K	-	local buckling coefficient; buckling coefficient of the compression flange
l	-	length of lip of C-section

L	-	span length; connection length
L_c	-	cover plate length
L_E	-	effective length
m	-	constant of elastic analysis of portal frame
M	-	bending moment for a loading system; bending moment acting at the action as F_v
M_b	-	buckling resistance moment
M_c	-	moment capacity of section
$M_c^{'}$	-	actual moment capacity
M_{cr}	-	critical bending moment
M_{exp}	-	experimental moment
M_{th}	-	theoretical moment
M_E	-	elastic lateral buckling resistance moment
M_r	-	moment in portal frame rafter
M_{re}	-	elastic moment in portal frame rafter
M_{rp}	-	plastic moment in portal frame rafter
M_l	-	moment in portal frame column
M_{le}	-	elastic moment in portal frame column
M_{lp}	-	plastic moment in portal frame column
M_p	-	plastic moment
M_x	-	moment at point X
M_c	-	moment capacity of section
M_{cr}	-	critical bending moment
n_1	-	length obtained by a 45º dispersion through half the depth of column
n_2	-	length obtained by a 1:2.5 dispersion through the column flange and root radius
N	-	constant of elastic analysis of portal frame; actual length of bearing; axial force
N_{exp}	-	experimental axial force
N_{th}	-	theoretical axial force
p_{cr}	-	local buckling stress of element
p_y	-	design strength

p_o	-	limiting compressive stress in a flat web
p_v	-	design strength
p_{vc}	-	design strength of column
P_c	-	resistance of column web in compression zone
P	-	applied point load
P_c	-	column web capacity in crushing/ bearing; column web capacity in buckling
P_{cf}	-	beam flange capacity in compression
P_{exp}	-	experimental ultimate load
P_{th}	-	theoretical ultimate load
P_{th}	-	theoretical ultimate load
P_{max}	-	ultimate load
P_s	-	theoretical ultimate load
P_t	-	tension capacity of unstiffened column web
P_{tc}	-	column web capacity in bending
P_{tf}	-	beam flange capacity in tension
P_{th}	-	ultimate load
P_v	-	shear capacity or shear buckling resistance
P_w	-	concentrated load resistance of a single web
q	-	constant generally 0.6 – 0.7
q_{cr}	-	shear buckling stress of a web
r	-	inside bend radius
r_c	-	column root radius
r_y	-	radius of gyration of section about Y axis
R_{mb}	-	moment ratio of beam
R_{mc}	-	moment ratio of connection
R_{ms}	-	ratio of strengthening moment
R_s	-	ratio of slope
R_t	-	ratio of section thickness
s	-	rafter length
sf	-	fillet weld leg length to beam flange
S	-	plastic modulus of section
S_{exp}	-	experimental curve slope

S_x	-	experimental curve slope about X-axis
S_{xr}	-	experimental curve slope
t	-	flange or web thickness; material thickness; compression element thickness
t_b	-	beam web thickness
t_{br}	-	thickness of bracing plate
t_c	-	thickness of cover plate; column web thickness
t_{eq}	-	equivalent thickness of section
t_p	-	thickness of stiffener plate
t_s	-	thickness of original section
T	-	flange thickness; tension force
T_b	-	beam flange thickness
T_c	-	column flange thickness
T_{exp}	-	experimental tension force
T_{th}	-	theoretical tension force
u	-	deflection of the centre of the flange towards the neutral axis
U_s	-	minimum ultimate tensile strength
V	-	vertical reaction of support; shear force
w	-	uniformly distributed load
x	-	points distance
$\bar{y}$	-	distance of flange from neutral axis
Y_s	-	minimum yield strength
Z	-	section modulus
Z_c	-	bending compression modulus for full cross section
Z_x	-	elastic modulus to X axis
α	-	coefficient of linear thermal expansion
β	-	ratio of the smaller end moment to the larger end moment M in the unbraced length of a beam
Δ	-	deflection for given loading system
Δ_c	-	deflection corresponding to M_c
Δ_{cr}	-	deflection of beam corresponding to M_{cr}
ε	-	constant
$\varnothing$	-	constant of elastic analysis of portal frame; rotation

η	-	Perry coefficient
θ	-	angle (in degrees) between plane of web and plane of bearing surface
υ	-	Poisson's ratio

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CHAPTER 1

INTRODUCTION

1.1 Overview

To date, the majority use of cold-formed steel on buildings is for roof and wall framing, cladding, purlins and railing with C channel, Z and I are the frequently used sections. As cold-formed steel sections are composed of thin elements, usually such sections are categorized as slender section due to the width to thickness b/T of the flange and depth to thickness d/t of the web ratios are relatively large. Thus, generally the sections are vulnerable to local buckling particularly on those compression elements subjected to bending or in axial compression.

In single storey industrial buildings, portal frames are a widely used typical structure because of their cleanliness, good overhead clearance and relatively low cost. Commonly, such frames are designed using plastic method to obtain an economical structure although the detailed stability check is required. So far, hot–rolled steel is the material which satisfies the requirement for such structures because of having ability to yield perfectly in tension as well as in compression. In addition, the hot-rolled connections have a sufficient rotational stiffness to form plastic hinge.

To expand the application of cold-formed steel in buildings, its use as portal frame members for replacing the hot-rolled needs to be considered. This is because cold-formed steel sections have advantages such as its light self-weight and corrosion-free problems. Otherwise, these are some weaknesses needed to be solved mainly due to the local buckling and low rotational stiffness connection.

1.1 Background of Research

The use of cold-formed steel sections as portal frame members of single storey industrial buildings is very rare. This mainly is due to their insufficient stability to withstand the large forces (i.e. horizontal force at the base, moment in the rafter and moment in the column) normally induced in portal frame structure. Previous studies (Vos and Rensburg, 1977; Lim and Nethercot, 2004; Kwon *et al*., 2006; Wilkinson, 2006) on this matter have not been performed extensively. Most existing research studied the cold-formed open sections subjected to bending or in compression of C channel, Z, L or I section (Adeli and Karim, 1997; Schafer and Pekoz, 1999; Pan and Yu, 2001; Corte *et al*., 2003; Young and Hancock, 2003; Yu and Schafer, 2003; Nguyen *et al*., 2006; Madry and Ignatowitcz, 2008). In addition, some researchers (LaBoube and Yu, 1998; Nuttayasakul and Easterling, 2006; Wood and Dawe, 2006; Dawe *et al*., 2009) have conducted researches on cold-formed steel sections for roof truss structure using a cold-formed lipped channel open section. In addition, a hat section was also used in the study by another researcher (Tahir *et al*., 2006).

The use of cold-formed closed section is an alternative to derive a better stability of section. A study on stability of the closed section had been performed by previous researchers but it was limited to the members subjected to bending (Serrette, 2004; Young and Chen, 2008; Xu *et al*., 2009). The only investigation on behaviour of cold-formed closed sections in portal frame had been carried-out. The study used cold-formed rectangular hollow sections with a relatively large thickness (Wilkinson, 2006). In fact, this type of section cannot be easily found in market. Therefore, it is a need to consider constructing a closed section by combining the existing and common sections.

A main weakness of applying cold-formed steel sections as portal frame members is the local buckling problem. This is because such sections are composed of thin elements in which the width to thickness *b*/*T* of the flange and depth to thickness *d*/*t* of the web ratios are relatively large. Consequently, in general cold-formed steel sections are categorized as slender section which causes buckling on the compression elements of the section at a stress level lower than the material yield strength. In order to prevent the local buckling, adding the thickness of the compression elements may be required.

In addition, another problem of applying cold-formed steel sections in portal frame besides the local buckling is low rotational stiffness of the connection. Although, all the types of the connections commonly used in hot-rolled steel structure can be applied to cold-formed steel, bolted connection is the type often used for the cold-formed moment connection. However, such connections can not be classified as rigid connection.

1.2 Problem Statement

This study is performed in order to enhance the use of cold-formed steel sections in buildings particularly for portal frame members. The main problems of applying such sections as portal frame members to be designed plastically are the local buckling and low rotational stiffness of the connection due to the local buckling.

Therefore, this research emphasize on how to prevent the local buckling of cold-formed steel sections so increasing the section capacity and how to improve the rotational stiffness of the connection. Thus, the problems to be solved of this study are the suitable section strengthening and connection methods of cold-formed steel particularly for portal frames have not been found.

The idea to strengthen cold-formed steel sections by adding the thickness of compression elements of the section in order to increase the section capacity is a relatively original concept. Likewise, the rigid connection of cold-formed members proposed by using cover plate is. Thus, this research is expected to increase the capacity of cold-formed steel sections. In addition, it is also expected that the proposed rigid connection can be achieved.

1.3 Objectives of Study

The objective of this study is to investigate the possibility of applying cold-formed steel sections in portal frame to be designed plastically. In detail, the objectives of this study are as follows:

(i) To generate design charts of pinned base portal frames;

(ii) To investigate analytically behaviour of cold-formed steel sections and its stability in portal frame;

(iii) To investigate experimentally effect of section strengthening and screw arrangements to the properties and capacity of small cold-formed steel beams;

(iv) To derive the design strength Y_s of the cold-formed and hot-rolled steel coupons;

(v) To investigate experimentally effect of the section strengthening method to the plastic section classification, section properties and capacity of strengthened cold-formed steel beams;

(vi) To investigate experimentally effect of the connection method to rigidity and capacity of the strengthened cold-formed steel connections.

1.4 Scope of Study

The scope of this research includes theoretical analysis and experimental test, which encompasses the following items:

(i) Elastic and plastic analysis diagrams of pinned base portal frame;

Portal frames with simply supported at the base, single storey and subjected to a uniformly distributed load were analyzed base on the elastic and plastic methods. The horizontal force at the base, moment in the rafter and moment in the column curves for elastic and same parameters for plastic with respect to rise/span and span/eaves height were generated.

(ii) Plasticity behaviour of cold-formed steel sections;

Six analytical studies were performed to investigate behaviour of cold-formed steel sections applied as portal frame members which were elastically and plastically analyzed. Stability of the rafter of open and closed sections was also checked. Effect of the B/D ratio to the plastic section classification of the cold-formed rectangular hollow section was determined. Properties and capacities of the cold-formed steel section and connections were calculated based on BS 5950 Part 5: 1998.

(iii) Capacity of strengthened cold-formed beams;

Three section types were used which are C channel, rectangular hollow and strengthened rectangular hollow sections. Plastic section classification, section properties and design capacity of the sections were calculated based on the design standard, BS 5950 Part 1: 2000 and BS 5950 Part 5: 1998. The experiment on six beams on C channel, rectangular hollow without strengthening and strengthened with hot-rolled plate was also performed. Form six beams, three rectangular hollow sections were strengthened by increasing the thickness of the web and compression flange using a splice of hot-rolled plate of 1 mm thickness. The plates were attached to the original section using self-driven screws. And the different number of screw and screw spacing were adopted. The results from theory and experimental were compared.

(iv) Performance of moment connection of the strengthened cold-formed members;

Three moment connections had been tested in this study i.e. welded, unbraced cover and braced cover connections. All the connections were strengthened by internal sleeve made of hot-rolled steel of 5 mm thickness. The connection members were closed sections formed of two channel sections which were face-to-face welded. The members were strengthened referring to the result of the strengthened cold-formed steel beam test. The connections were tested by applying horizontal point load on the rolled point on the connections edge. Maximum load, deflection and rotation adjacent to the observed point of the connection were recorded. Moment-rotation diagrams, rigidity and capacity of the connections were obtained. The experimental and theoretical results were compared.

1.5 Organization of Thesis

This thesis is structured as follows: Chapter 2 contains a literature review which covers basic theory and previous studies on portal frame analysis, cold-formed steel stability, strengthening of cold-formed steel sections and portal frame connections. The chapter provides the basis to draw the portal frame analysis diagrams and overall review of cold-formed steel members subjected to bending. In addition, some methods of steel section strengthening and rigid connection concept are described. Chapter 3 discusses the analytical study on structure and elements of cold-formed steel portal frame. Chapter 4 outlines the experimental study using model while Chapter 5 and Chapter 6 explain the full-scale study has been performed. Results obtained from this research and the discussion is presented in Chapter 7. Finally, Chapter 8 provides some conclusions and suggestions for further study.

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