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AN INVESTIGATION OF THE COMPRESSIVE STRENGTH OF COLD-FORMED STEEL BUILT-UP I SECTIONS

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KEYWORDS

Built-up, Cold-formed steel, Finite Element Method, Direct Strength Method, Effective Width Method.

ABSTRACT

Cold-formed steel members have been used extensively in low and mid-rise residential building construction. The usage of cold-formed steels as primary structural members has been increased due to its high load to weight ratio. Cold-formed steel built-up sections are commonly used as compression elements to carry larger loads and over longer spans when a single individual section is insufficient. However, not much research has been done on built-up sections. This paper aims to investigate the compressive capacity of pin-ended cold-formed steel built-up I sections using the finite element method (FEM). In the study, cold-formed steel built up I section consists of two identical C-channels sections oriented back to back forming an I-shaped cross section and connected to each other at certain spacing along their length. A non-linear finite element model is developed and verified against theoretical and experimental results. The theoretical numerical analysis is based on the Effective Width Method and the Direct Strength Method. As for the experimental testing, the compression test is carried out on 11 specimens. It was shown that the finite element methods results correlate well with the experimental results. In addition, the analytical results by the Effective Width Method and Direct Strength Method are generally conservative for cold-formed steel built-up I sections.

INTRODUCTION

Cold-formed steel has been used widely across many countries in the construction industry. Cold-formed steel has been utilized in various forms in construction projects. The built-up section is one of the most used cold formed steel sections when single sections are no longer sufficient to cater for the advancement and complexity in construction industry. Built-up sections can be any two or more sections connected together e.g. back-to-back built-up I sections (Figure 1). These cold-formed built-up sections are commonly used as compression members such as columns, or members of roof trusses in buildings. However, very few studies have been carried out to study the built up cold-formed steel sections [1], [2]. The use of these built-up sections leads to complex design problems. The complexity is due to the interactive buckling characteristic of built-up members under load. In order to account for these buckling behaviours, a specific provision for design of built-up sections was introduced in section C4.5 of the 2001 edition of American Iron and Steel Institute (AISI) North American Specification for the Design of Cold Formed Steel Structural Members [3]. This specification is substantially based on the research of hot rolled steel despite the characteristics of hot rolled steel being considerably different from cold-formed steel.

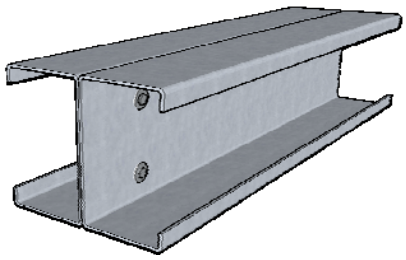

Figure 1: Lipped Back-to-back Built-up I Sections

DESIGN APPROACH

The three design approaches i.e. EWM, DSM I, and DSM II are based on two well known methods i.e. Effective Width Methods (EWM) and Direct Strength Methods (DSM) derived in North American Specifications (NAS) 2001 [3].

EWM

In this study, EWM utilizes the concept of individual elements and neglects the interaction between the plate elements where for a single C-channel, web is stiffened, flange is edge stiffened and lip is unstiffened. The degree of stiffening affects the calculation of effective area, A_e. In built-up sections, NAS 2001 assumes that both channels are of the same stiffening effect. Therefore, the assumption made for effective area of built-up section is simply twice that of a single C-channel i.e. $A_{eb} = 2A_{ec}$. In terms of slenderness ratio, the provision in Specification Section C4.5 of NAS 2001 requires that for compression members composed of two sections in contact, the nominal axial strength shall be determined by replacing KL/r with $(KL/r)_m$. This is to account for the buckling failures that induce shear forces in the connectors between individual shapes. This spacing requirement $a/r_i \leq 0.5(KL/r)_o$ is being used to account for ineffective and loose bolts or screw [3]. Thus, in the nominal axial strength determination, modified slenderness ratio, $(KL/r)_m$ is used to determine buckling stress, F_e.

$$\left(\frac{KL}{r}\right)_m = \sqrt{\left(\frac{KL}{r}\right)_o^2 + \left(\frac{a}{r_i}\right)^2} \tag{1}$$

where, $\left(\frac{KL}{r}\right)_o$ = Overall slenderness ratio of entire section about built-up member axis, a = Intermediate fastener or spot weld spacing, r_i = Minimum radius of gyration of full unreduced cross-sectional area of an individual shape in a built-up member.

DSM I & II

DSM does not require complex effective area calculations as in EWM. It provides a flexible design procedure so that it simplifies the analysis of complex sections. It predicts member strength based on member's elastic buckling loads. The first DSM approach in this study (i.e. DSM I) uses manual hand calculation from the design manual in determination of elastic buckling load. Modifications on slenderness ratio (same as EWM) were introduced to calculate critical Euler buckling stress (F_e). For DSM II, finite strip analysis software, CUFSM, is used to determine P_{crl} and P_{crd}. For both DSM I and DSM II, P_{crl} and P_{crd} are simply twice the single cross-section value in the built-up cross section, thus, analysis was done by analysing a simple C-lipped channel. However, P_y/P_{cre} differs because torsional-flexural mode is replaced by a separate torsion mode and a strong-axis flexure mode. Due to difficulties to determine P_y/P_{cre} from CUFSM curve, hand calculation methods were used. The finite strip analysis software – CUFSM used in this research was introduced by Schafer to predict the strength ratio [5]. The first minima of the curve reveals load ratio for local buckling where as the second minimum point shows load ratio for distortional buckling.

Finite Element Analysis

The general concept of finite element analysis (FEA) is the principle of discretization (sub-dividing). Complex model geometry is analysed by sub-dividing them into finite elements which connecting to each other by nodes in order to perform the analysis. In this study, cold-formed steel built-up sections were modelled using commercial finite element software, LUSAS 14.0 and the model is built based on the geometric properties of the cold formed steel built-up sections. The self-drilling screws connecting the built-up sections were assumed as small thin steel strips. Since the thickness to width or depth ratio of the cold-formed steel section is relatively small, surface-like element was used to represent the structures. Therefore, thin shell element QSL8 is selected as suggested by Farzin et al. [6]. QSL8 is a semi-loof shell which comprising of 6 or 8 numbers of anticlockwise nodes, each with 3 degrees of freedom.

EXPERIMENT PROGRAM

Specimen

Laboratory tests were performed on 11 specimens of back-to-back built-up I sections. The test specimens were brake-pressed from high strength zinc-coated grade G450 structural steel sheets of 1.6 mm thickness. The nominal yield strength and Young's modulus for these specimens are 450MPa and 200GPa. The test program comprised of three series of lipped back-to-back built-up columns. All these built up specimens had a standard length of 1600mm, web width of 100mm, lip of 20mm and flange width of 50mm. The variable is the screw spacing along the column length i.e. 750, 1000, 1500mm.

Figure 2 clearly illustrates the test specimen.

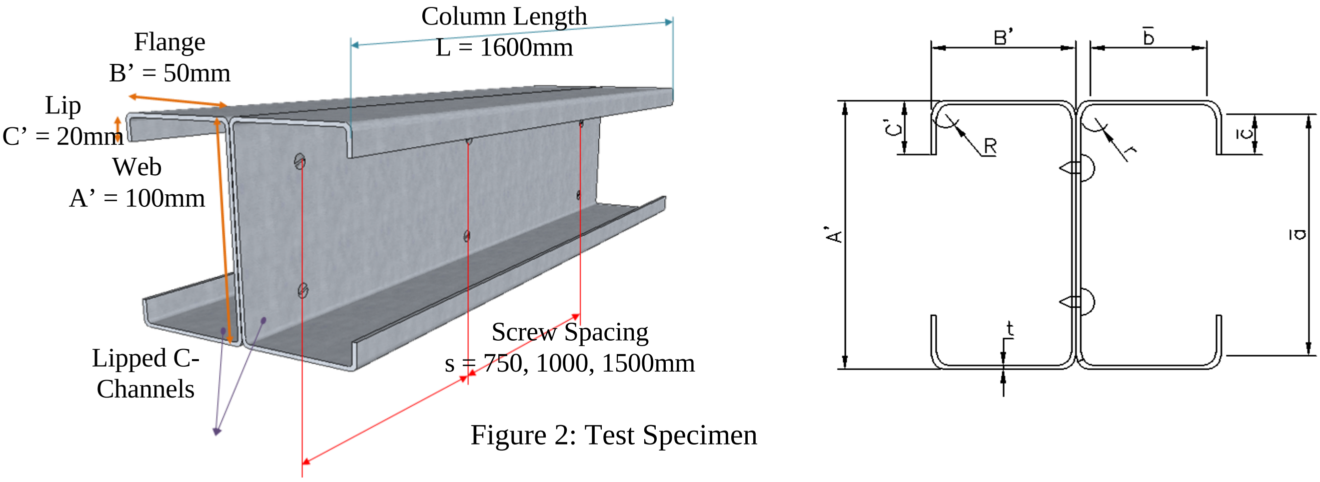

Figure 2: Test Specimen

The three series were labelled BU750, BU1000, BU1500 where ''BU'' refers to ''built-up'' whereas 750, 1000 and 1500 refers to screw spacing. The average values of measured cross-section dimensions of the pin-ended test specimens are shown in

All specimens were tested in axial compression with pinned end conditions. Compressive axial force was applied to the specimen using a 50 tonne hydraulic jack system. The specimens, end plates and ball bearings were then arranged concentrically. This is to minimise the loading imperfections. A schematic of the test setup is shown in Figure 3. Pre-load of less than 6kN was applied so that the specimen is fully in contact with the end plates. This is to hold the test setup in position and to eliminate any possible gap and movements between the end plates and the specimen. Three Low Voltage Displacement Transducer (LVDT)s were each positioned at mid span of web, mid span of flange and the steel plate extended from top of the specimen to measure deflection of web, deflection of flange and shortening of specimen respectively. Readings were recorded at every 1 second interval.

Table 1. Not all of the built up specimen meet the fastener spacing provisions in AISI specification section D1.2.

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TABLE 1
AVERAGE MEASURED SPECIMEN DIMENSIONS

Specimen	**A'** **mm**	**B'** **mm**	**C'** **mm**	**t** **mm**	**R** **mm**	**L** **mm**	**s** **mm**
BU 750-1	104.0	48.5	20.0	1.55	2.5	1600	750
BU 750-2	104.0	48.5	19.5	1.55	2.5	1600	750
BU 1000-1	103.0	49.0	20.0	1.55	2.5	1600	1000
BU 1000-2	103.0	49.0	20.0	1.55	2.5	1600	1000
BU 1000-3	102.0	50.5	19.0	1.55	2.5	1600	1000
BU 1500-1	105.0	47.5	20.0	1.55	2.5	1600	1500
BU 1500-2	104.5	48.5	20.0	1.55	2.5	1600	1500
BU 1500-3	104.0	49.0	19.5	1.55	2.5	1600	1500
BU 1500-4	104.0	48.5	19.5	1.55	2.5	1600	500
BU 1500-5	104.0	48.0	20.0	1.55	2.5	1600	500
BU 1500-6	104.0	48.5	19.5	1.55	2.5	1600	750

** Rounded up to the nearest 0.5mm.*

Test Setup

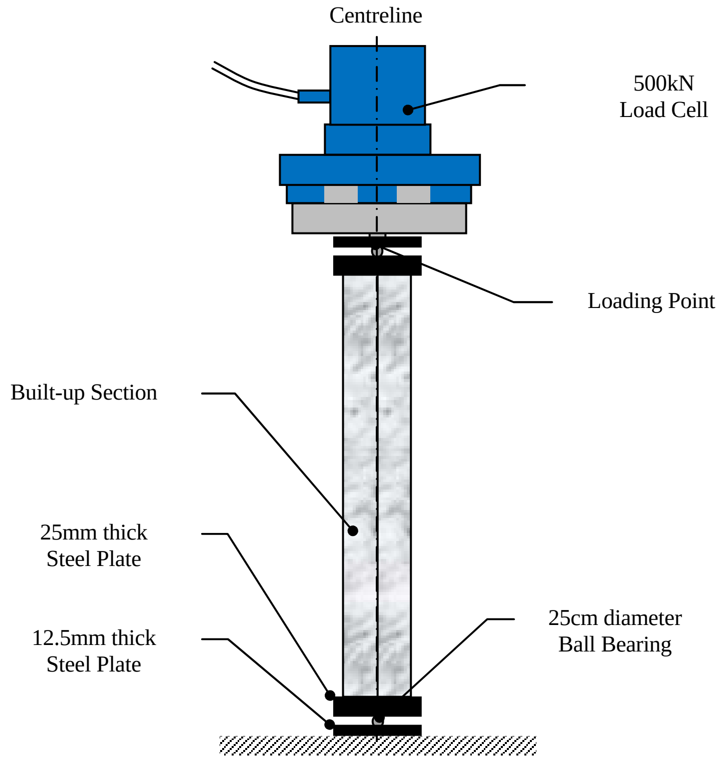

Figure 3: Schematic of Test Setup

RESULTS & DISCUSSION

Analytical compressive strength results using finite element (LUSAS), Direct Strength Method (DSM) and Effective Width Method (EWM) for BU750, BU1000, and BU1500 series were tabulated in Table 2. The experimental local buckling load was determined using the method according to Venkataramaiah and Rorda (7). The load (N) against the square of local buckling deformation (w) graph was plotted. In this case the web deformation at mid-length was use. Then a line is subsequently fitted through the test points in the post buckling region. The interception with the load axis resulting from the line was assumed to be the experimental buckling load.

TABLE 2
ANALYTICAL RESULTS OF BUILT-UP I SECTIONS

Specimen	P_{LUSAS}	P_{DSMI}	P_{DSMII}	P_{EWM}
BU 1500	129.4	106.2	118.4	115.8
BU 1000	168.6	131.0	146.5	152.7
BU 750	170.3	140.9	157.8	168.2

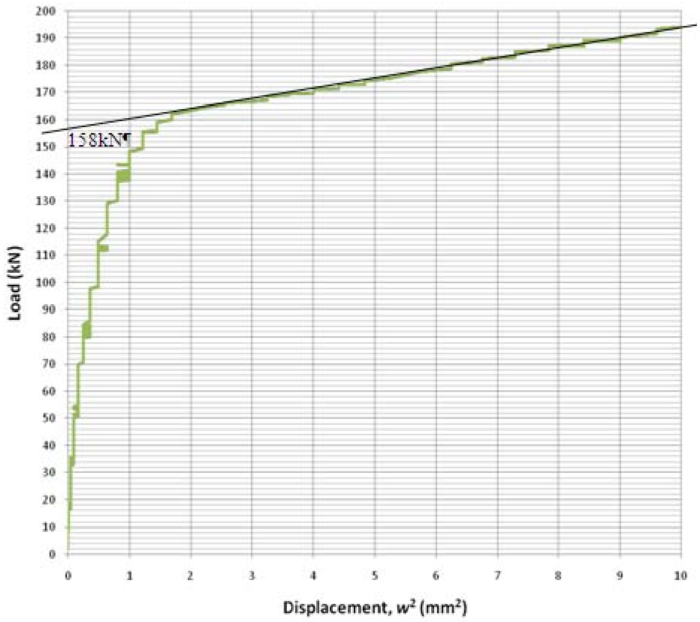

Figure 4: Load vs the square of local buckling deformation for BU1000-1

BU750 Series

Experimental results for BU750 series are tabulated in Table 3.

TABLE 3
RESULTS OF BU750 SERIES

Specimen	P_{EXP}	$\frac{P_{EXP}}{P_{LUSAS}}$	$\frac{P_{EXP}}{P_{DSMI}}$	$\frac{P_{EXP}}{P_{DSMII}}$	$\frac{P_{EXP}}{P_{EWM}}$
BU750-1	170.0	1.00	1.21	1.08	1.01
BU750-2	160.0	0.94	1.14	1.01	0.95
Average		0.97	1.17	1.05	0.98

The experimental results show good correlation with finite element method results as shown in Figure 5. However, these finite element method results by LUSAS 14.0 are un-conservative compared to Direct Strength Method. The experimental compressive strengths for this series of columns are generally in between the prediction by LUSAS and EWM results. Whereas Direct Strength results, DSM I and DSM II are relatively conservative.

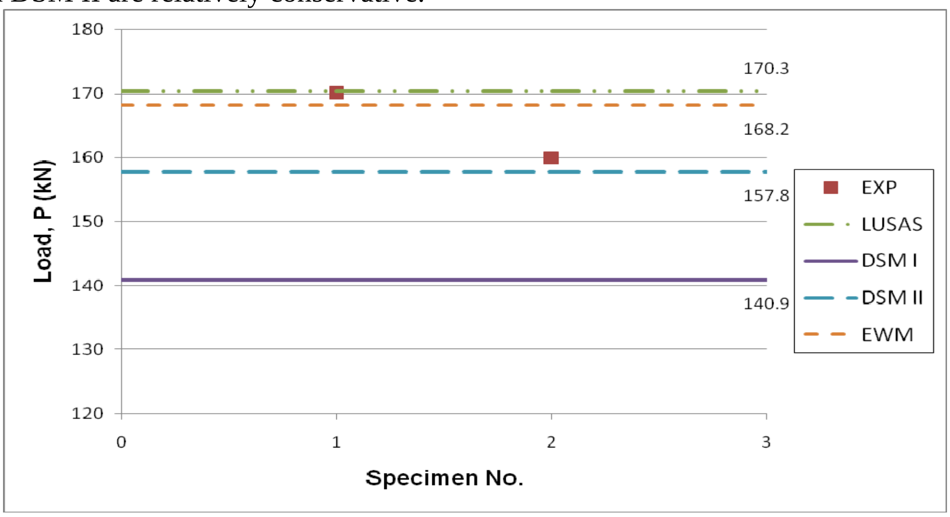

Figure 5: Results for BU750 Series

BU1000 Series
Experimental results for BU1000 series are tabulated in Table 4.

TABLE 4
RESULTS OF BU1000 SERIES

Specimen	P_{EXP}	$\frac{P_{EXP}}{P_{LUSAS}}$	$\frac{P_{EXP}}{P_{DSMI}}$	$\frac{P_{EXP}}{P_{DSMII}}$	$\frac{P_{EXP}}{P_{EWM}}$
BU1000-1	158.0	0.94	1.21	1.08	1.03
BU1000-2	164.0	0.97	1.25	1.12	1.07
BU1000-3	168.0	1.00	1.28	1.15	1.10
Average		0.97	1.25	1.11	1.07

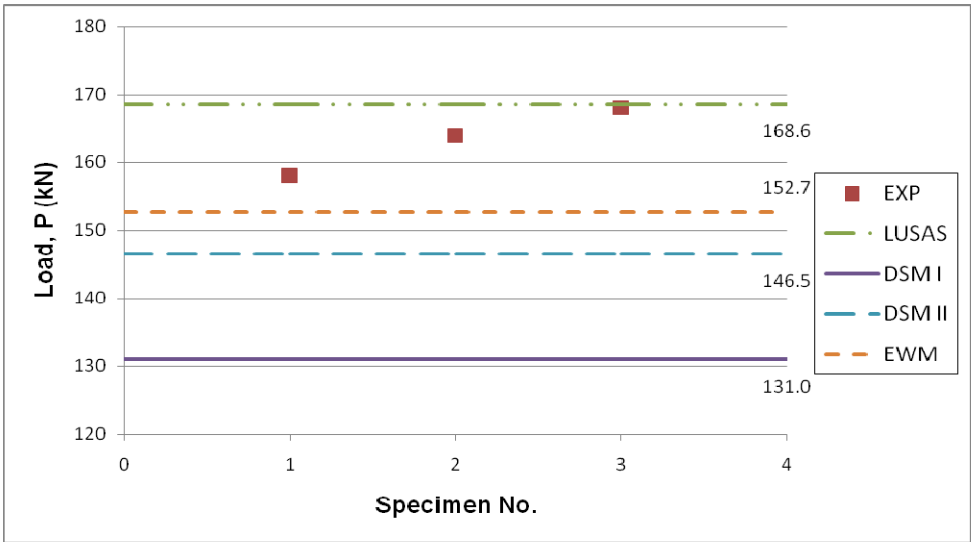

Figure 6: Results for BU1000 Series

Although the finite element results correlate well with the experimental results, they are generally un-conservative compared to EWM, DSM II, and DSM I results. As shown in Figure 6, Effective Width method predicts the compressive strengths for this series well whereas the Direct Strength method results, DSM I and DSM II are more conservative.

BU1500 Series

Table 5 shows that finite element method results predict well the compressive capacity of the built-up I sections compared to EWM, DSM I, and DSM II results. Figure 7 shows that finite element results are not un-conservative like in BU750 and BU1000 series. Besides, the DSM II results correlate better compared to EWM in this series.

TABLE 5
RESULTS OF BU1500 SERIES

Specimen	P_{EXP}	$\frac{P_{EXP}}{P_{LUSAS}}$	$\frac{P_{EXP}}{P_{DSMI}}$	$\frac{P_{EXP}}{P_{DSMII}}$	$\frac{P_{EXP}}{P_{EWM}}$
BU1500-1	128.0	0.99	1.21	1.08	1.11
BU1500-2	140.0	1.08	1.32	1.18	1.21
BU1500-3	132.0	1.02	1.24	1.12	1.14
BU1500-4	125.0	0.97	1.18	1.06	1.08
BU1500-5	140.0	1.08	1.32	1.18	1.21
BU1500-6	124.0	0.96	1.17	1.05	1.07
Average		1.02	1.24	1.11	1.14

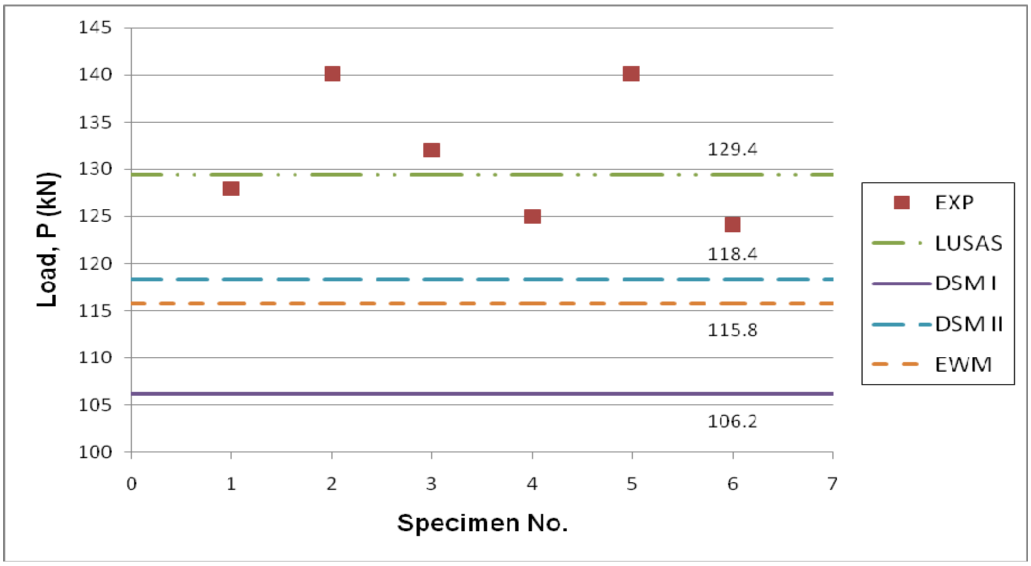

Figure 7: Results for BU1500 Series

BU1500-2 and BU1500-5 had shown higher strength than other specimens in the series. From the laboratory observations, these sections buckled at mid-span. It is also noticed that the lipped C-channels for both BU1500-2 and BU1500-5 buckled concentrically in opposite directions. In terms of built-up I section, these two sections buckled in the strong axis. Whereas others may not be secured enough by the screws to allow the built-up I section to behave as one integral section. Therefore, reducing the compressive strength of the section

CONCLUSION

Theoretical analysis was carried out on 11 specimens of built-up I sections. Three design approaches (EWM, DSM I, and DSM II) based on two methods i.e.Effective Width Method (EWM) and Direct Strength Method (DSM) with the help of finite strip analysis software (CUFSM) were used to analyse the built-up I sections. In addition, finite element modelling was carried out. Finite elements method results show good correlations with the experimental results compared to EWM and DSM results. In general, DSM results are conservative as compared to EWM results for shorter build-up I sections however more study is needed for a consistent design of cold-formed steel built up sections.

(a) BU1000 (b) BU1500

Figure 8: Deformed Mesh in FEA and buckling in Testing

ACKNOWLEDGEMENTS
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