Strength Enhancements in Tensile Properties of Steel by Press Brake Cold Forming

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1 Introduction

The cold-formed steel built-up Hybrid Double-I-Box Beams (HDIBBs) are made of different grades of steel sheets done by Deepak et al. [1, 2]. In this study, the steel sheets manufactured employing both hot-rolled and cold-rolled processes are used. The sections are formed by press braking operation. The amount of cold work varies for each segment in the different regions of the cross section. Ananthi et al. [3, 4] studied the behaviour of cold-formed structural steel in compression using medium strength steel. Knowing the exact material properties sheets (before forming) and sections (after forming) as essential to evaluate the tensile strength and stress–strain characteristics of each segment in a cold-formed steel member. Afshan et al. [5] conducted material testing programme on various grades of steel materials to evaluate the strength enhancements in cold-formed structural steel sections that arise during different methods of manufacturing processes. They proposed predictive models to estimate the increase in yield strength during manufacture of cold-formed steel sections. The method offers on an average of 19% and 36% strength enhancements comparative to the minimum codified strength as provided in the European standards. Chen and Young [6] assessed the feasibility of current design standards available for the design of stainless-steel structures. They reported that the tensile strength predictions by existing specifications are conservative and can be reliable. Ho et al. [7] reported that steels with same grades but made of different manufacturing processes possess deformation properties. Xiong and Liew [8] from their research reported that

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high strength steel has smaller comparative thermal elongation and higher reductions of effective yield strength and elastic modulus at raised temperatures. In this study, the coupon specimens are prepared and tested according to the guidelines provided in European standards EN ISO 6892-1-2009 [9]. The stress–strain graphs are drawn for the tested coupon pieces and their properties are inferred from the plots. The results obtained are compared with the equivalent international standards and mill certificates provided by the manufacturer.

2 Research Significance

The material properties and engineering stress–strain characteristics obtained from these tensile tests are converted into true stress–strain values and can be provided as input in the modelling of finite element models, for performing the numerical analysis. The bending residual stresses are re-introduced due to forming. The paper gives a clear idea on the characteristics of commonly used steel materials for research and production purposes.

3 Steel Products

The sheet metal is manufactured by TATA steel (P) limited India and procured from Govindaraja Mudaliyar Sons, suppliers, Chennai. The supplier provided the mill certificates mentioning the grade of steel (G). The steel products and their equivalent European standards are as tabulated in (Table 1). In the present study, the prime interest is on European standards as the metallurgy and manufacturing technology of the products comply with EN 10,025 and EN 10,130.

4 Coupon Specimens' Preparation

Flat coupons in two groups are prepared and tested. The first group consists of are cut from the flat sheets before forming in three different regions, namely, longitudinal, transverse and diagonal directions. The second group consists of coupons which are extracted from different flat portions of the channels. At least two coupons are cut tested from each group of the sections to find out the average results; therefore, the error is minimised. The effect of cold work forming at the corners is not included in this study. All the tensile coupons specimens are prepared, sized and tested according to recommendations suggested in EN ISO 6892–1-2009 [9] standards. Coupons are sized using the available machining facilities. Accurate measurements of the cross sections, length, width and thickness are made using a digital Vernier calliper. Typical prepared coupon specimens are shown in (Fig. 1). Based on the gripped end width

Table 1 Product specifications and their equivalent European standards

Tata product name and size, L × B × t (mm)	Classification		Strength as per manufacturer		Elongation percentage	Nominal strength as per European code		Equivalent standards
	Product	Type	f_y (N/mm^2)	f_u (N/mm^2)	%	f_y (N/mm^2)	f_u (N/mm^2)	European
CRSHEET-ICF TATXXD AU03-2500 × 1250 × 2.5 mm	Cold Rolled (CR)	Low Tensile (LT)	140/ 220	280	35	140/180	270/330	EN 10,130: 2006 DC03 CR
HRC IS2062E250Fe410 WGrASME-2500 × 1250 × 2.5 mm	Hot Rolled (HR)	Medium Tensile (MT)	255	410	23	245	380	EN 10,025 Part 2:2004 S275 JO
HR COIL DIN17100ST52.3 SH-ECA-2500 × 1250 × 2.5 mm	Hot Rolled (HR)	High Tensile (HT)	355	490	22	310	450	EN 10,025 Part 2:2004 S355 JO

(a) Machined and sized coupons

(b) Surface cleaned coupons

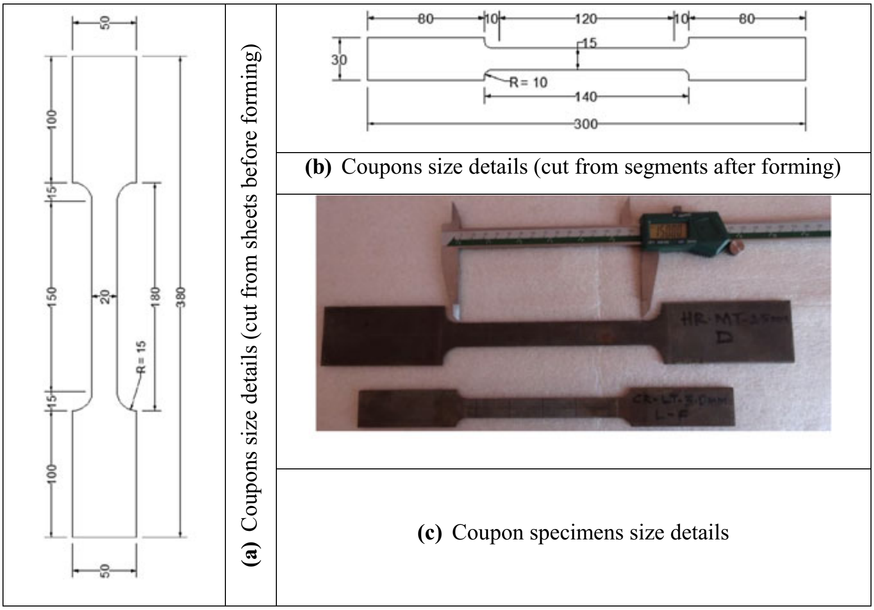
(c) Marked coupons

Fig. 1 Prepared coupon specimens

and the required parallel width of the specimen, the radius of the cutting is provided. The larger is the size of the coupons (parallel length and width), the greater is the precision. The coupon sizes are illustrated in (Fig. 2).

5 Test Set-Up and Instrumentation

The tests are performed using a Zwick/RoellZ100kN Electro-mechanical testing machine. The tensile test set-up for testing coupon specimens is shown in (Fig. 3). According to the procedure recommended in EN ISO 6982-1-2009 International standards, displacement control method of testing is adopted. The uniform crosshead displacement rate applied is 0.01 mm/s in the present investigation since the materials tested are having $E = 200{,}000\ N/mm^2$ or higher. Necking of coupons within the gauge length is observed due to the application of tensile load during testing, just before fracture. The testing of coupons and failure of a typical coupon specimen under tensile load is illustrated in (Fig. 4).



(a) Coupons size details (cut from sheets before forming)

(b) Coupons size details (cut from segments after forming)

(c) Coupon specimens size details

Fig. 2 Sizing of coupons

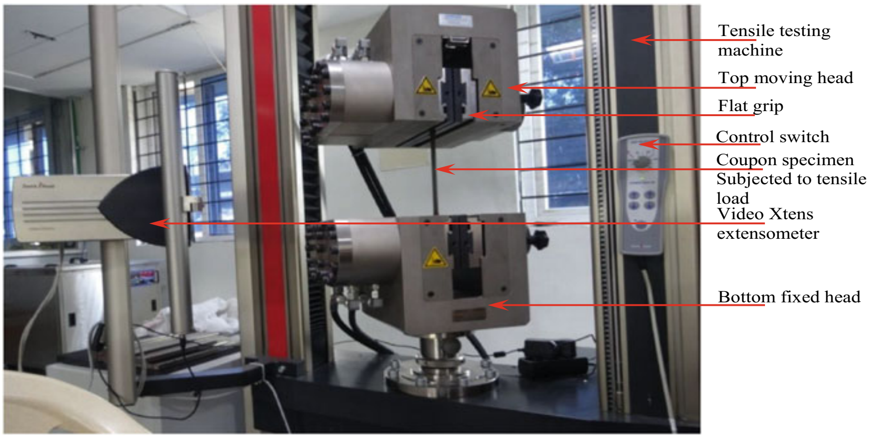


Fig. 3 Tensile test set-up

6 Results and Discussion on Tensile Properties of Materials

The static stress–strain plots are automatically generated and recorded for all the tests. Three key parameters are obtained they are the yield stress (f_y), the ultimate stress (f_u) and the best-fit modulus of elasticity (E). The comparison of stress–strain

Fig. 4 Failure of a coupon under tensile load

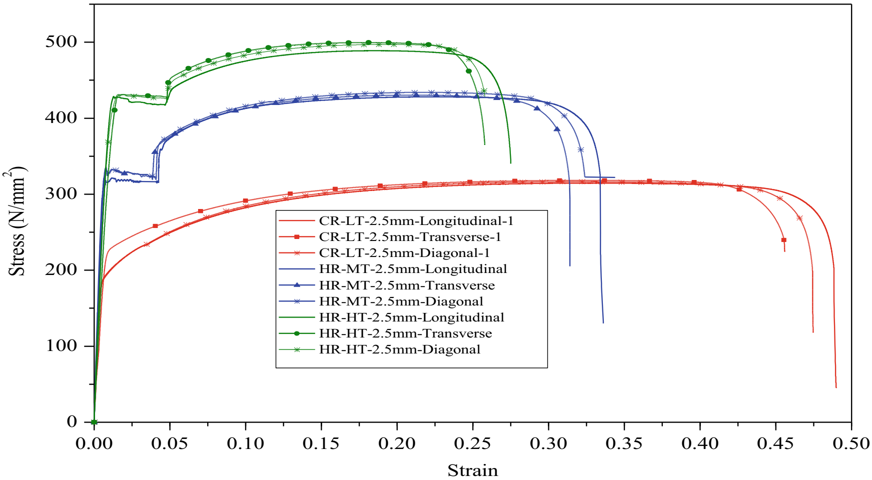


Fig. 5 Comparison of stress–strain characteristics of the sheet cut coupons

characteristics for 2.5 mm thick sheet cut coupons that are cut in all three directions from all three grades of steel are shown in (Fig. 5).

6.1 Material Properties of Coupons Extracted from Steel Sheets Before Forming

Large size coupons are cut in three directions, namely, longitudinal, transverse and diagonal directions from the steel sheets of size 2500 × 1250 mm and 2.5 mm think including all grades. The tensile test results for sheet cut coupons before forming is given in (Table 2). The cold-rolled-low tensile strength (CR-LT) steel material showed a gradual stress–strain response in which there a well-defined yield point is absent, hence 0.2% proof stress is taken as yield stress. The hot-rolled-medium tensile (HR-MT) and hot-rolled-high tensile (HR-HT) strength steel materials exhibited a sharp response; hence, their yield stresses are taken from a well-defined yield point.

6.1.1 Tensile Test Results of CR-LT Steel Sheets

The properties for nominal grade G140 cold-rolled steel sheets (DC03 CR) is confirming to Eurocode standards EN 10,130: 2006. The nominal basic yield strength (f_{yb}), of CR-LT sheets, is taken as 140 MPa according to (Table 3) of Eurocode EN

Table 2 Tensile test results of sheet cut coupons before forming

Classification as per eurocode standards	Location of strip cut	Thickness (mm)	Width B (mm)	Yield stress, f_y (N/mm^2)	Ultimate stress, f_u (N/mm^2)	Ratio, f_u/f_y	Elasticity modulus, E (GPa)
Group-1 (CR- LT)	Longitudinal	2.50	20.01	211.29	304.85	1.44	207
EN10130: 2006 DC03 CR	Transverse	2.49	20.01	226.37	308.08	1.36	206
Steel Grade: G 140	Diagonal	2.50	20.00	215.42	306.38	1.42	207
Group-2 (HR- MT)	Longitudinal	2.50	20.00	315.09	428.12	1.36	215
EN 10,025 Part 2:2004 S275 JO	Transverse	2.50	20.01	319.17	430.27	1.35	214
Steel Grade: G 245	Diagonal	2.50	20.02	318.83	421.49	1.32	215
Group-3 (HR- HT)	Longitudinal	2.50	20.01	417.10	494.08	1.18	221
EN 10,025 Part 2:2004 S355 JO	Transverse	2.49	20.02	420.80	499.52	1.21	221
Steel Grade: G 310	Diagonal	2.50	20.01	418.97	497.02	1.17	218

Table 3 Tensile test results of section cut coupons after forming

Classification as per Eurocode standards	Location of strip cut	Thickness (mm)	Width B (mm)	Yield stress, f_y (N/mm^2)	Ultimate stress, f_u (N/mm^2)	Ratio, f_u/f_y	Elasticity modulus, E (GPa)
Group-1 (CR- LT)	Flange –L-1	2.50	15.01	234.61	339.43	1.45	211
Steel grade: G 140	Flange –L-2	2.50	15.00	230.65	338.44	1.47	215
	Web –L-1	2.50	15.02	236.79	319.74	1.35	209
	Web –L-2	2.50	15.01	232.83	317.76	1.37	210
					Mean:	1.41	
Group-2 (HR- MT)	Flange –L-1	2.50	15.00	337.56	432.73	1.27	213
Steel grade: G 245	Flange –L-2	2.50	15.01	337.66	429.72	1.27	212
					Mean:	1.27	
Group-3 (HR- HT)	Flange –L-1	2.50	15.01	463.48	510.79	1.11	220
Steel Grade: G 310	Flange –L-2	2.50	15.00	459.52	503.86	1.11	221
*L—Long channel sections-2500 mm					Mean:	1.11	

3.1.3, that is given for materials used in forming structural sections that are not mentioned in the design standard. At first, for coupons cut in the longitudinal direction, the range of yield stress is between 211 and 222 MPa, and the range of ultimate stresses is between 305 and 320 MPa. The experimental yield stresses are on an average 50% higher than the nominal basic strength which is limited to 140Mpa. Secondly, for coupons cut in the transverse direction, the range of yield stresses is between 226 and 240 MPa, and the range of ultimate stresses is between 308 and 324 MPa. The experimental yield stresses are on an average 61% higher. Thirdly, for coupons cut in the diagonal direction, the range of yield stresses is between 215 and 234 MPa, and the range of ultimate stresses is between 306 and 321 MPa. The experimental yield stresses are at least 53% higher.

6.1.2 Tensile Test Results of HR-MT Steel Sheets

The properties for nominal grade G245 hot-rolled steel sheets (S275 JO-HR) are confirming to Eurocode standards EN 10,025 Part 2: 2004. The nominal basic yield strength of HR-MT sheets is taken as 275 MPa according to (Table 3) of EN 3.1.3. At first, for coupons cut in the longitudinal direction, the range of yield stresses is between 315 and 352 MPa, and the range of ultimate stresses is between 428 and

453 MPa. The experimental yield stresses are at least 15% higher than basic strength that is limited to 275 MPa; Secondly, for coupons cut in the transverse direction, the range of yield stresses is between 319Mpa and 357 MPa, and the range of ultimate stresses is between 430 and 468 MPa. The yield stresses are on average 16% higher. Thirdly, for coupons cut in the diagonal direction, the range of yield stresses is between 319 and 354 MPa, and the range of ultimate stresses is between 421 and 457 MPa. The measured yield stresses are at least 16% higher.

6.1.3 Tensile Test Results of HR-HT Steel Sheets

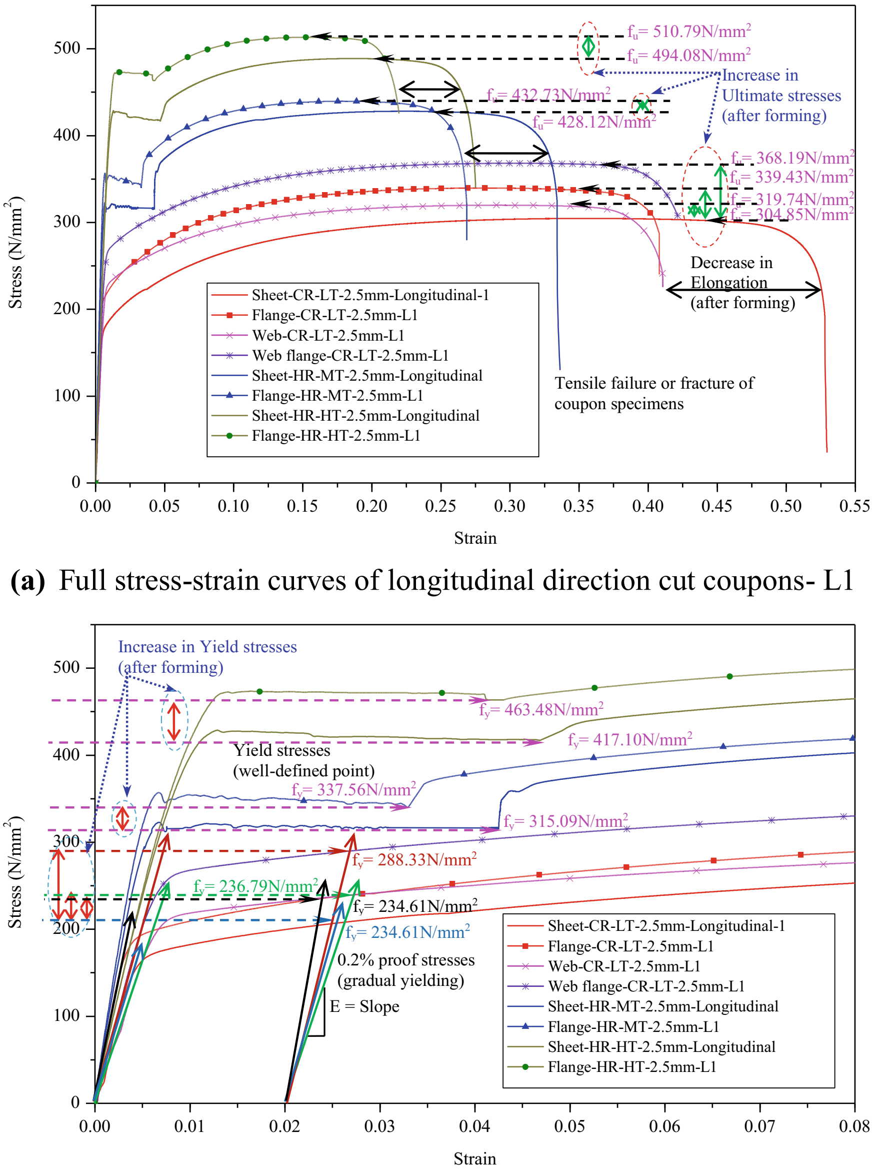
The properties for nominal grade G310 hot-rolled steel sheets (S355 JO-HR) are confirming to Eurocode standard EN 10,025 Part 2:2004 [10]. The nominal basic yield strength of HR-HT sheets is taken as 310 MPa according to (Table 3) of EN 3.1.3. At first, for coupons cut in the longitudinal direction, the range of yield stresses is between 417 and 429 MPa, and the range of ultimate stresses is between 494 and 505 MPa. The experimental yield stresses are at least 34% higher than basic strength that is limited to 310 MPa. Secondly, for coupons cut in the transverse direction, the range of yield stresses is between 421 and 423 MPa, and the range of ultimate stresses is between 500 and 513 MPa. The yield stresses are at least 35% higher. Thirdly, for coupons cut in diagonal the direction, the range of yield stresses is between 419 and 423 MPa, and the range of ultimate stresses is between 497 and 506 MPa. The yield stresses are at least 35% higher.

6.2 Material Properties of Coupons Extracted from Steel Sections After Forming

The CFS channels are 2500 mm long formed from the longitudinal direction of the steel sheet. The tensile tests result for section cut coupons after forming are given in (Table 3). Typical comparison plots showing stress–strain behaviour of sheet cut coupons (before forming) and section cut coupons (after forming) are illustrated in (Fig. 6).

6.2.1 Tensile Test Results of CR-LT Steel Sections

The properties of coupons for nominal grade G140 (i.e. CR-LT) cut from the flanges and web portions of the formed long channels, the yield stresses are in the range of 231 MPa and 235 MPa, and the range of ultimate stresses is 318 MPa and 340 MPa. The yield stresses are at least 10% higher than those obtained from testing longitudinal direction sheet cut coupons. This increase in stresses indicates that a substantial amount of cold work done. The elasticity modulus obtained from the tests is between



(a) Full stress-strain curves of longitudinal direction cut coupons- L1

(b) Initial part of stress-strain curves- L1

Fig. 6 Comparison of stress–strain characteristics of 2.5 mm thick longitudinal direction cut coupons—L1 (before and after forming)

209 and 215GPa. The average ratio of ultimate strength to yield stress, $f_u/f_y = 1.41$ which is greater than 1.10 as recommended by EN 3.1.1 clause 3.2.2. This, shows that these cold-rolled sheets have good ductility behaviour. A large elongation and necking are observed before failure while testing of coupon specimens that exhibits CR-LT possesses high ductility behaviour.

6.2.2 Tensile Test Results of HR-MT Steel Sections

The properties of coupons for nominal grade G245 (i.e. HR-MT) cut from cut from the flange portions of the formed long channels, the yield stresses are in the range of 337 MPa and 338 MPa, and the range of ultimate stresses is 430 MPa and 433 MPa. The experimental yield stresses are 9% higher than those determined coupons tests from sheets. The modulus of elasticity obtained from the tests is between 212 and 213GPa. The average ratio of ultimate strength to yield stress, $f_u/f_y = 1.27$ which is greater than 1.10. This shows that these medium tensile-grade hot-rolled sheets have reasonable ductility behaviour. Average elongation and necking of coupon specimens occurred before failure while testing exhibiting normal ductility behaviour in HR-MT-grade steel sections.

6.2.3 Tensile Test Results of HR-HT Steel Sections

The properties of coupons for nominal grade G310 (i.e. HR-MT) cut from flange portions of the formed channels in longitudinal direction, the yield stresses are in the range of 460 MPa and 464 MPa, and the range of ultimate stresses is 504 MPa and 511 MPa. The experimental yield stresses are on at least 9% higher than those obtained by testing coupons cut from sheets in the longitudinal direction. The elasticity modulus obtained from the tests is between 220 and 221GPa. The average ratio of ultimate strength to yield stress, $f_u/ f_y = 1.11$ which is greater than 1.10. This shows that this high strength-hot-rolled steel has less ductility behaviour. Low elongation and quick fracture of coupon specimens are observed while testing. These fracture characteristics display low ductility in HR-HT-grade steel sections. Fracture of coupon specimens both before and after forming is shown in (Fig. 7).

7 Conclusion

A series of experimental tests to determine the tensile properties of various grades of steel materials by testing their coupons extracted from the steel sheets before forming and from the various segments of the sections after forming have been conducted in this study. The following are the findings depicted based on the tensile test results of coupons and their characteristic stress–strain plots.

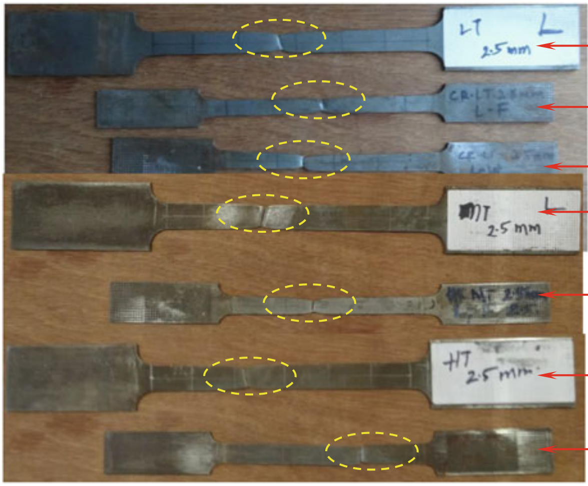


Fig. 7 Experimental fracture of 2.5 mm thick longitudinal direction cut coupons—L1 (before and after forming)

- In the sheet cut coupons testing from the results obtained, it is evident that there exists a marginal material anisotropy. The yield point strength and ultimate strength of tested coupons cut in transverse direction is slightly higher in comparison to those from longitudinal and diagonal directions. The coupons cut from longitudinal direction showed the minimum strength for all grades of steel.
- On comparison of the stress–strain plots cold-rolled process manufactured steel materials exhibited a gradual stress–strain response, whereas hot-rolled process manufactured products showed sharp definite yield point characteristics.
- The yield strengths and the ultimate strength of the plates are increased after press braking the sheets formed into sections. The higher the cold-forming at the segments the higher is the increase in their yield strength.
- The percentage increase in ultimate strength of the steel sheets formed into sections in longitudinal direction considered in this research are such that (i) for CR-LT steel grade, the increase is 10%, (ii) for HRMT steel grade, the increase is 9% and (iii) for HRHT steel grade, the increase is 9%
- The ductility is reduced after forming, whereas the elasticity modulus is enhanced.

References

1. Deepak MS, Shanthi VM (2018) Distortional buckling moment resistance capacity of hybrid-double-i-box beams. J Struct Eng 144(9)
2. Deepak MS, Shanthi VM (2018) Member distortional buckling behaviour of hybrid-double-i-box beams. Can J Civ Eng 45:605–622

3. Ananthi GBG, Roy K, Chen B, Lim JBP (2019) Testing, simulation and design of back-to-back built-up cold-formed steel unequal angle sections under axial compression, Steel and composite structures. Int J 33(4): 595–614
4. Ananthi GBG, Deepak MS, Roy K, Lim JBP (2021) Influence of intermediate stiffeners on the axial capacity of cold-formed steel back-to-back built-up unequal angle sections. Structures 32: 827–848
5. Afshan S (2013) Rossi, B and Gardner, L 'Strength enhancements in cold-formed structural sections - Part I: material testing.' J Constr Steel Res 83:177–188
6. Chen M-T, Young B (2020) Tensile tests of cold-formed stainless-steel tubes. J Struct Eng 146(9):04020165
7. Ho HC, Chung KF, Liu X, Xiao M, Nethercot DA (2019) Modelling tensile tests on high strength S690 steel materials undergoing large deformations. Eng Struct 192:305–322
8. Xiong M-X, Richard Liew JY (2016) Mechanical properties of heat-treated high tensile structural steel at elevated temperatures. Thin-Walled Struct 98:169–176
9. European Committee for Standardization (CEN) (2009) Metallic materials—Tensile testing—part 1: method of test at room temperature'. EN ISO 6892-1, Brussels. Belgium
10. European Committee for Standardization (CEN) (2005) 'Eurocode 3: Design of steel structures-part 1–1: general rules and rules for buildings, EN 1993-1-1. Belgium, Brussels