Malaysian Journal Of
Civil Engineering

BENDING RESISTANCE OF HIGH STRENGTH HOT-ROLLED STEEL UNIVERSAL COLUMN SECTION

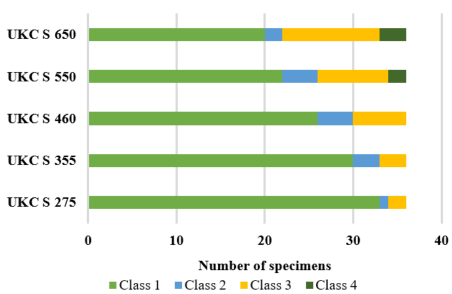
Chen Tat Chung, Jian Jun Moy, Cher Siang Tan*, Arizu Sulaiman

Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia.

Article history
Received
07 March 2023
Received in revised form
20 May 2023
Accepted
21 May 2023
Published online
30 July 2023

*Corresponding author
tcsiang@utm.my

Graphical abstract



Abstract

The most commonly found steel grades in the market are S 275 and S 355 However, recent advancement in the welding techniques allows for the development of high-strength steel for higher grades up to S 700 with reasonable cost and quality to construct heavy-loaded and long spanned structures. To facilitate the selection of the section sizes in accordance to Eurocode 3 Standard, this research focusses on investigate and validate the bending resistance, $M_{c,Rd}$ and lateral torsional buckling resistance, $M_{b,Rd}$ of a hot-rolled steel universal column section (UKC) from common steel grades (S 275 and S 355) up to high strength steels (S 460, S 550 and S 650). This study employed Microsoft Excel spreadsheet to develop a program for design calculation for UKC in accordance with Eurocode 3 Standard and compared with the available results provided in SCI P363. The validated program was further applied to develop selection data for high strength UKC steels (S 460, S 550 and S 650). The study outcome suggests that the classification, $M_{c,Rd}$ and $M_{b,Rd}$ of the steel is greatly affected by the steel grade. The parametric study in this research also shows that C_1 factor, section size and span length can also affect the $M_{c,Rd}$ and $M_{b,Rd}$ of the steel, aside from steel grade. Further analysis of high strength UKC steels was done and tabulated since the program developed was validated and employed in the study.

Keywords: Bending resistance, lateral torsional buckling resistance, Universal Column Section (UKC), high strength steel, parametric study.

1.0 INTRODUCTION

Hot-rolled steel and cold-formed steel have been a critical material in construction for many years, providing strength and durability required for various structural applications. Both steel were differentiated by their manufacturing process. In Malaysia, most used hot-rolled steel were the I-section, L-section, C-section, T-section, and various shape of hollow sections etc. which can be found in SCI P363 [1]. Furthermore, with advancements in manufacturing and material technology, high strength steel, HSS (yield strength higher than 460 MPa) has become increasingly popular in the construction industry for e.g. high-rise buildings and long span bridges in the past two decades due to its improved mechanical properties and potential for cost savings [2]. Based on study by Y. B. Wang et al. [2], the application of HSS members can allow the use of smaller cross section members and save building spaces, reducing the workloads of transportation and welding and shortening the time of construction.

In a steel structure building, additional loads from the ceiling, walls, floors and etc. were transferred and distributed through the structural components of the building like beams and columns. The load transfer then affects the behaviour of the beam structurally, which can be represented as shear, bending and torsion. The structural components was then being designed to evaluate the resistance towards the forces based on the combination of the section dimensions, the material properties of the steel in accordance to the code of practices like Eurocode 3, BS EN 1993-1-1 [3]. Within the construction industry, universal column sections (UKC) were widely used as a vertical structural element, providing supports for the horizontal components of the building. However, UKC can be vulnerable to bending loads, which can cause them to deform critically in the building. Hence, attention should be given to the design of UKC, including appropriate sizing and reinforcement to enhance their resistance to bending forces and mitigate the risk of detrimental deformations.

According to the literatures, numerous studies have highlighted the behaviour of steel structures under bending. The study of S. Chen [4] investigates different methods to design for local buckling behaviour of the HSS I-section under bending forces. The finding of the study suggests that in certain design strength, f_y, the design expressions of this study offer more accurate and less scattered prediction compared to Eurocode 3 [3] specification which was further being evaluated with reliability analysis in accordance to BS EN 1990 [5]. Moreover, the study of Li Shuai et al. [6] further investigates the behaviour and resistances of hot-rolled stainless steel C-section under combined compression and minor-axis bending moment by conducting experimental and numerical studies. The outcome of the study proposes the design interaction curves for designing the stainless-steel sections that were improved in design accuracy and consistency. To further facilitate the selection of steel section, SCI P363 [1] included the member resistance table which includes the resistance for compression, tension, bending, web bearing and buckling, axial force and bending, bolt and fillet welds for steel grades S 275 and S 355. However, further advancement of the steel manufacturing has improved the steel material properties from S 460 to S 650. Hence, it was suggested that further expansion of the current member resistance table to more steel grade is beneficial towards the industry.

This study focussed on the analytical study of the effect of various UKC dimensions on the member bending capacities including bending resistance, $M_{c,Rd}$ and lateral torsional buckling resistance, $M_{b,Rd}$. The bending capacities of the UKC were calculated based on Eurocode 3 specification using self-developed program in Microsoft Excel and were compiled as a "masterlist" for future applications which includes expanding the table of resistances ($M_{c,Rd}$ and $M_{b,Rd}$) incorporating higher steel grades (S 460, S 550, and S 650).

2.0 METHODOLOGY

The methodology of the study involves the investigation of section properties of hot-rolled UKC; data validation of $M_{c,Rd}$ and $M_{b,Rd}$ for common steel grade S 275 and S 355; analytical study of HSS UKC utilizing self-developed program in Microsoft Excel; and a parametric study.

2.1 Investigation of Section Properties of hot-rolled UKC

Based on SCI P363 [1], it was found that 36 specimens of hot-rolled UKC section was listed with the section designation ranging from 356 x 406 x 634 kg/m to 152 x 152 x 23 kg/m with the length between lateral restraints varies from 2.0 m to 14.0 m and C1 value varies from 1.00 to 2.50. The tabulated lists of the UKC sections consists of two parts: basic dimensions and geometrical properties for the listed sections. Both tables mentioned above were applied during the section selection for building structural members. Besides, this table can provide a quick and clear reference for an engineer to ease the data selection.

Furthermore, Section 3 of Eurocode 3 further explains the materials properties and requirements of structural steel. It was found that the common structural steel is categorized into four grades related to its nominal values of design strength, (f_y) which are S 235, S 275, S 355 and S 450 which are based on the material standard stated in BS EN 10025-2 [7].

However, further findings from the standard shows that BS EN 1993-1-12 [8] includes additional rules for the extension of EN 1993-1-1 [3] up to steel grades S 700. This additional standard were published to add on new steel grade details of Eurocode 3 on year 2007.

2.2 Data Validation of $M_{c,Rd}$ and $M_{b,Rd}$ for common steel grade S 275 and S 355

In this study, a program was developed utilising Microsoft Excel to calculate the $M_{c,Rd}$ and $M_{b,Rd}$ for UKC sections. The design calculation was based on the standard code of practice EN 1993-1-1 specifications [3]. To validate the data in the program, tabulation list of lateral torsional buckling resistance of S 275 and S 355 UKC steel sections was found in SCI P363 [1] and its data was used for comparison with the calculated lateral torsional buckling resistance. The parameters include the steel dimensions, length between lateral restraints, and C1 values. The percentage difference between the data from P363 [1] and manual calculation were shown and was categorised in five categories which includes $\leq$ 5%, $\leq$ 10%, $\leq$ 15%, $\leq$ 20%, and $\leq$ 25%.

2.3 Further calculation of $M_{c,Rd}$ and $M_{b,Rd}$ for steel grade S 460, S 550, and S 650

Upon the validation of the excel program, the $M_{c,Rd}$ and $M_{b,Rd}$ of the HSS UKC steel section were calculated utilizing it. A master lists was developed for the results from steel grade S 275 to S 650, which facilitates engineers to quickly decides the UKC section size by looking at the tabulations.

2.4 Parametric study

In the parametric study, the difference between the resistances due to steel grades, section size and span length of the specimen was compared and discussed. From the result and discussions, graphs and tabulation were shown for better comprehension.

3.0 RESULT AND DISCUSSION

A total of 36 UKC steel specimens were classified with its bending resistance calculated and tabulated in a table with length varies from 2 m to 14 m at 1 m interval for steel ranged from 356 × 406 × 634 kg/m to 203 × 203 × 86 kg/m in a Microsoft Excel spreadsheet. For steel ranged from 203 × 203 × 71 kg/m to 152 × 152 × 23 kg/m, the range of length were set from 1 m to 10 m where 0.5 m interval for length 1 m to 4 m and 1 m interval for length 4 m to 10 m. In addition, the C1 factor 1.0, 1.5 and 2.0 in the design calculation of lateral torsional buckling resistance were calculated and tabulated for comparison for steel grade S 275 and S 355. Parametric study was applied for higher grade of steel which are UKC grade S 460, S 550 and S 650.

The final design data (bending resistance, lateral torsional buckling resistance) of the UKC steel specimens for S 275, S 355, S 460, S 550, S 650 were then linked and tabulated in a master list. The master lists were titled as "Masterlist for steel grade" and was shown at the end of discussions.

3.1 Results for All Grade of UKC Section Grade

Lateral torsional buckling resistance, $M_{b,Rd}$ was calculated with varying length and C_1 factor 1, 1.13, 1.35, 1.5, 1.77, 2 and 2.5 for UKC section grade S 275. The results were done to validate the distribution of data between the calculated flexural resistance and the data tabulated in the SCI P363 Steel Building Design: Design Data. For other UKC grades, C_1 factor 1, 1.5, and 2 were used for simplification purposes.

Based on the comparison for the lateral torsional buckling resistance, $M_{b,Rd}$ between the calculated data and SCI P363 Steel Building Design: Design Data for common steel, S 275 and S 355, the percentage difference was calculated and summarized as shown in Figure 1. It was found that for S 275 steel, the percentage difference is less than or equal to 10% for 83% of all data and for S 355 steel the percentage difference is less than or equal to 10% for 72% of all data. The difference was due to the roundoff of calculated data in between the steps of design calculation, the values of input data being used for calculations and the difference in steps of design calculation etc. In the list of properties for UKC sections, the plastic modulus W_{pl} (used in Class 1 UKC and Class 2 UKC) and elastic modulus W_{el} (used in Class 3 UKC) was shown and used as input data for the program, which will be one of the factor causing the difference. Nevertheless, based on the summary of percentage difference, the data from the developed program was considered accurate and was valid to continue for the following design calculation for high strength steel.

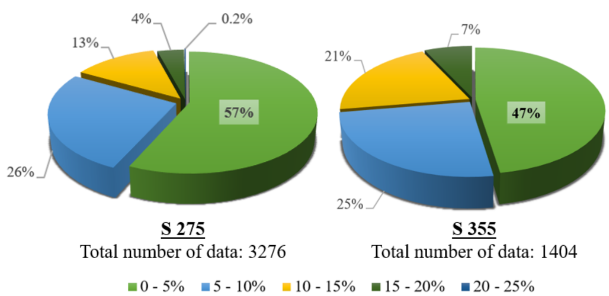


Figure 1: Illustration of percentage difference of results from developed excel program and SCI P363 Table.

For high strength steel, S 460, S 550 and S 650, the calculated data shows that the bending resistance, $M_{c,Rd}$ and lateral torsional buckling resistance, $M_{b,Rd}$ of the UKC section possess similar trend for all specimen in which the data is observed increasing over the increment of C_1 factor and decrease over the reduction of size and length increment of UKC section which was shown in Figure 2, Figure 3 and Figure 4.

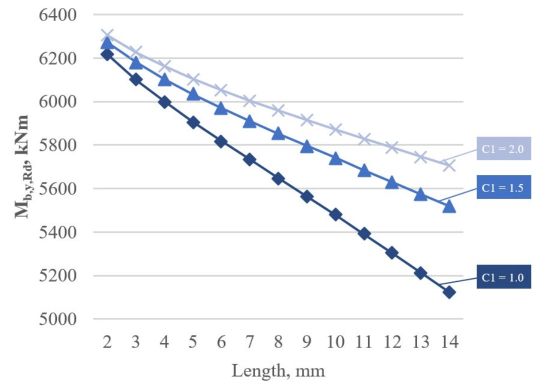


Figure 2: Graph of length versus lateral torsional buckling resistance included with C_1 value for HSS UKC S 460 (UKC 356 × 406 × 634 kg/m)

3.2 Comparison

3.2.1 Section Classification

Referring to Figure 5, it was found that UKC S 275 has total of 33 UKC steels classified as Class 1. The number of Class 1 UKC has reduced as the steel grade increases. On the contrary, the number of Class 3 UKC increased as the steel grade increases. Furthermore, it was found that only S 550 and S 650 resulted with some of the UKC classified as Class 4. Further investigation on this finding suggests that the formula (Eq. 1) found in EN 1993-1-1 Clause 4.2.1.1 to be the cause of the results. The ε value will decrease as the steel grade, f_y increase and subsequently causing the limiting value of each class to become smaller in while the ratio for local buckling (flange and web) remains constant at all grade.

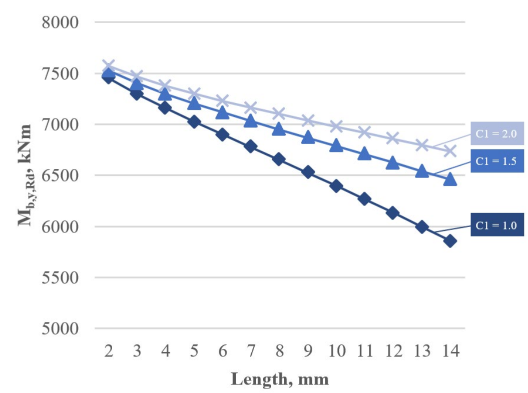


Figure 3: Graph of length versus lateral torsional buckling resistance included with C_1 value for HSS UKC S 550 (UKC 356 × 406 × 634 kg/m)

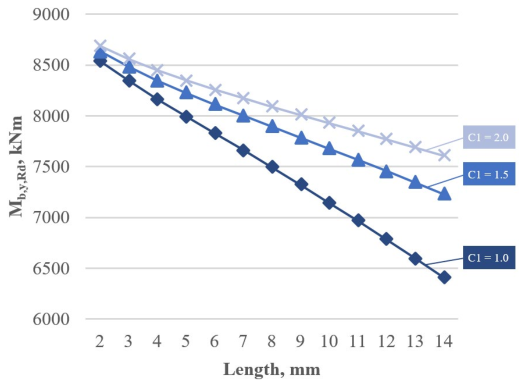


Figure 4: Graph of length versus lateral torsional buckling resistance included with C_1 value for HSS UKC S 650 (UKC 356 × 406 × 634 kg/m)

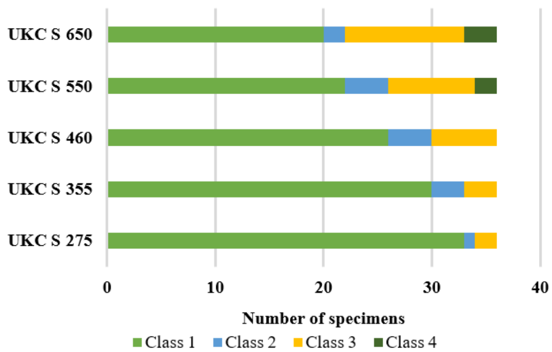


Figure 5: Illustration of UKC Section vs Classification Distribution

$$\varepsilon = \sqrt{\frac{235}{f_y}} \qquad \text{Eq. 1}$$

3.2.2 Analytical Study on Lateral Torsional Buckling Resistance

From the analytical study of the design calculation for lateral torsional moment resistance, it was found that the higher the steel grade, the higher the calculated λ_{LT} and Φ_{LT}, which in the end resulted with a lower value of χ_{LT}. Subsequently, lower the value of χ_{LT} affected the value of lateral torsional buckling resistance $M_{b,Rd}$ although the steel strength was increased. Hence, the higher steel strength will not guarantee a higher lateral torsional buckling resistance, $M_{b,Rd}$ of the UKC sections. However, since bending resistance $M_{c,Rd}$ is not affected by length but only steel grade, it will remain the same for the particular UKC section with same grade and different length. Figure 6 shows the summary and illustration of the lateral torsional buckling resistance and bending resistance procedure chart with the sketches based on the discussion in this section.

3.2.3 Parametric Study

For parametric study and analytical investigation on UKC section grade S 275, S 355, S 460, S 550 and S 650, the calculated data shows that the bending resistance $M_{c,Rd}$ and lateral torsional buckling resistance $M_{b,Rd}$ of the UKC section possess similar trend for all specimen in which the data was observed increasing over the increment of C_1 factor, and decrease over the reduction of size and length increment of UKC section. By comparing the UKC section of all grade S 275, S 355 S 460, S 550 and S 650,with the same C_1 factor, the calculated data for lateral torsional buckling resistance $M_{b,Rd}$ increased as the steel grade go higher as shown in Figure 7. Referring to Figure 8, the calculated data shows that the bending resistance $M_{c,Rd}$ showed similar trend as the lateral torsional buckling resistance $M_{b,Rd}$ where the resistance increased as the steel grade increased. The data for all steel grades were combined and listed in the “Development of Masterlist for S275, S355, S460, S550, S650”. Table 1 shows an example of the summarized table for UKC 356 x 406 x 634 kg/m.

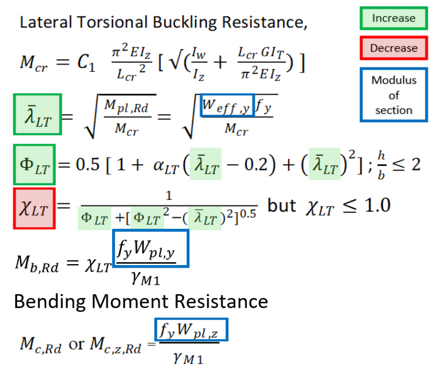


Figure 6: Summary of calculation procedure for lateral torsional buckling resistance and bending resistance of UKC Section.

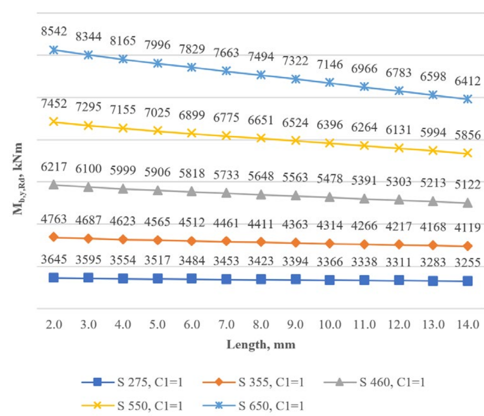


Figure 7: Distribution of calculated lateral torsional buckling resistance $M_{c,Rd}$ vs length for UKC 356 × 406 × 634, C_1 factor=1

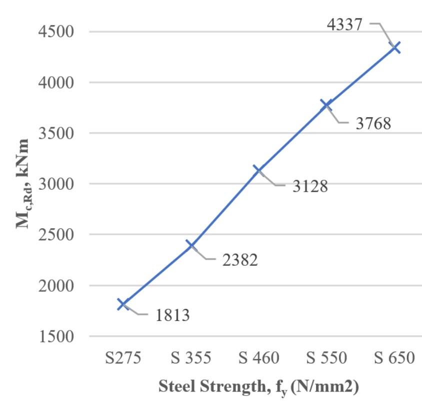


Figure 8: Calculated bending resistance $M_{c,Rd}$ vs steel strength for UKC 356 × 406 × 634 kg/m

Table 1: Masterlist for UKC 356 × 406 × 634 kg/m with steel grades S 275, S 355, S 460, S 550, S 650

Designation	Steel Grade	Class	C1	$M_{b,Rd}$, kNm													$M_{c,Rd}$, kNm	Second Moment of Area y-y axis, Iy (mm^4)
				2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0		
356×406×634	S 275	Class 1	1.0	3645	3595	3554	3517	3484	3453	3423	3394	3366	3338	3311	3283	3255	1813	275000
356×406×634	S 275	Class 1	1.5	3669	3629	3596	3568	3542	3519	3497	3476	3456	3436	3417	3398	3380	1813	275000
356×406×634	S 275	Class 1	2.0	3684	3649	3621	3597	3575	3556	3538	3520	3504	3488	3473	3458	3443	1813	275000
356×406×634	S 355	Class 1	1.0	4763	4687	4623	4565	4512	4461	4411	4363	4314	4266	4217	4168	4119	2382	275000
356×406×634	S 355	Class 1	1.5	4800	4739	4689	4645	4605	4567	4532	4498	4465	4433	4401	4369	4337	2382	275000
356×406×634	S 355	Class 1	2.0	4822	4769	4726	4689	4656	4626	4597	4570	4544	4518	4493	4469	4445	2382	275000
356×406×634	S 460	Class 1	1.0	6217	6100	5999	5906	5818	5733	5648	5563	5478	5391	5303	5213	5122	3128	275000
356×406×634	S 460	Class 1	1.5	6273	6180	6102	6033	5970	5910	5852	5796	5740	5685	5630	5574	5519	3128	275000
356×406×634	S 460	Class 1	2.0	6306	6227	6161	6104	6052	6003	5958	5914	5871	5829	5787	5746	5705	3128	275000
356×406×634	S 550	Class 1	1.0	7452	7295	7155	7025	6899	6775	6651	6524	6396	6264	6131	5994	5856	3768	275000
356×406×634	S 550	Class 1	1.5	7527	7403	7298	7203	7115	7031	6948	6867	6787	6705	6624	6541	6457	3768	275000
356×406×634	S 550	Class 1	2.0	7570	7465	7377	7299	7228	7162	7098	7036	6975	6915	6855	6795	6735	3768	275000
356×406×634	S 650	Class 1	1.0	8542	8344	8165	7996	7829	7663	7494	7322	7146	6966	6783	6598	6412	4337	275000
356×406×634	S 650	Class 1	1.5	8635	8481	8348	8227	8113	8003	7895	7787	7678	7569	7458	7345	7230	4337	275000
356×406×634	S 650	Class 1	2.0	8690	8559	8448	8350	8259	8173	8091	8010	7930	7850	7770	7690	7609	4337	275000

4.0 CONCLUSIONS

Based on the data validated and tabulated, the following observations and conclusions have been made:

1. It was found that when the steel strength increases, the classification of the steel calculated were more prone to be class 3 section. Furthermore, only high strength steel (S 550 and S 650) resulted with Class 4 sections.
2. Regardless of the steel grade of the UKC section, the elastic critical moment, M_{cr} for lateral-torsional buckling design remains constant. However, the valueof λ_{LT} and ϕ_{LT} were affected which lowered the value of χ_{LT} resulting with a lower lateral torsional buckling resistance of the section. Thus, the steel grades in UKC can directly affect the lateral torsional buckling resistance.
3. From the validation study of S 275 and S 355 the percentage difference between the calculated lateral torsional buckling resistance and SCI P363 data is observed to be alongside the increment of C1 value and length. However, the validation has shown that the program developed was valid.
4. Based on the parametric study and analytical study on high strength UKC steel (S 460, S 550 and S 650), the bending resistance and the lateral torsional buckling resistance of the UKC section increases over the increment of C1 factor. However, the resistances decreased over the reduction of sectional size and span length of the UKC.
5. Further comparison of UKC section based on all steel grades (S 275, S 355, S 460, S 550 and S 650) showed that the lateral torsional buckling and the bending moment resistance of the UKC increased as the steel grade increases.

Acknowledgements

The authors would like to express appreciation for the financial support of Universiti Teknologi Malaysia (UTM-FR 21H47 and 21H68).

References

[1] E. Nunez-Moreno and E. Yandzio, 2009."Steel building design: Design data "Eurocode Blue Book"(P363)," *SCI, Tata Steel, BCSA,* 590,

[2] Y.-B. Wang, G.-Q. Li, S.-W. Chen, and F.-F. Sun, 2012, "Experimental and numerical study on the behavior of axially compressed high strength steel columns with H-section," *Engineering Structures,* 43: 149-159, 2012/10/01/ doi: https://doi.org/10.1016/j.engstruct.2012.05.018.

[3] B. Standard, 2006. "Eurocode 3—Design of steel structures—," *BS EN 1993-1,* 1: 2005,

[4] S. Chen, H. Fang, J.-z. Liu, and T.-M. Chan, "Design for local buckling behaviour of welded high strength steel I-sections under bending," *Thin-Walled Structures,* 172: 108792, 2022/03/01/ 2022, doi: https://doi.org/10.1016/j.tws.2021.108792.

[5] BSI, 2005. "BS EN 1990: 2002+ A1: 2005–Basis of Structural Design"

[6] S. Li, L. Zhang, and O. Zhao, 2022. "Testing, modelling and design of hot-rolled stainless steel channel sections under combined compression and minor-axis bending moment," *Thin-Walled Structures,* 172: 108836, 2022/03/01/ doi: https://doi.org/10.1016/j.tws.2021.108836.

[7] B. EN, 2004."10025-2: 2004, Hot rolled products of structural steels," *Technical delivery conditions for non-alloy structural steels, BSI,* 17,

Alam, J.B., Dikshit, A.K., and Bandyopadhyay, M. 2004. Sorption and Desorption of 2, 4-D and Atrazine from Water Environment by Waste Tyre Rubber Granules and Its Management. *Global NEST: the International Journal,* 6: 105-115.