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DEVELOPMENT OF A COMPUTER PROGRAM FOR THE DESIGN OF LATERALLY UNRESTRAINED STEEL BEAMS

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Abstract. *This study presents the design results of a C-sharp based computer program developed for the design of laterally unrestrained I-section steel beams. The program was developed based on the stipulations of BS 5950 and Eurocode 3 (EC3) design standards. Several sets of steel beam models having the same cross-sectional dimensions but different laterally unrestrained span lengths, were designed using the developed program, and the results were validated using an established software, Staad Pro. The design results obtained were found similar to the results obtained using Staad Pro. For a specific beam section with constant loadings, as the span length of the laterally unrestrained compression flange increases the buckling capacity reduces, thus the longer the beam, the more it is susceptible to lateral torsional buckling. Comparison of the results obtained using BS 5950 to those of EC 3 at different laterally unrestrained span lengths revealed that the areas of design sections obtained for BS 5950 are 21.5%, on the average, higher than those of EC3. Thus, beams with laterally unrestrained compression flange designed according to the requirements of EC 3 are more economical. The difference in results is because of the differences in the principles of design and measures used between the two standards.*

Key words: *laterally unrestrained beams, Eurocode 3, BS 5950, C-sharp, lateral torsional buckling*

INTRODUCTION

Over the course of history, structural engineers have made significant contributions and improvements to the environment we live in today. As the prices of materials continue to increase, engineers are forced to reduce the costs of construction and shorten the implementation period to maintain their competitiveness. As a result, a new design trend was born: the use of the analysis and design software to evaluate feasible design options,

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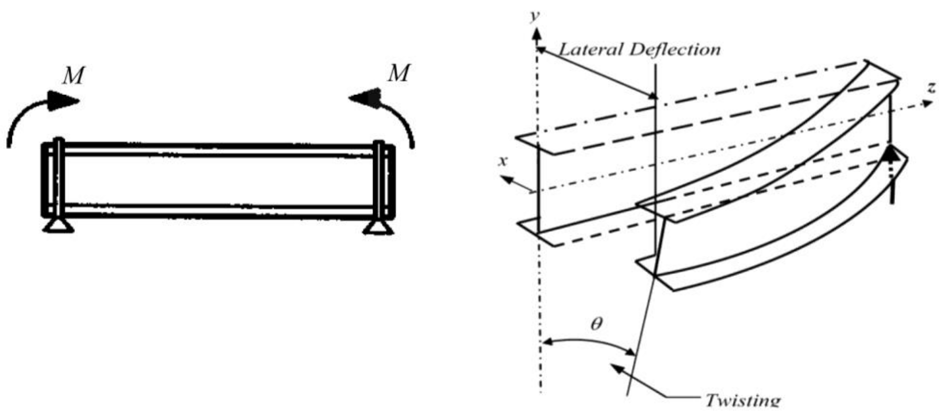
replacing the conventional design methods [1]. The introduction of software usage in the structural engineering industry has greatly reduced the complexities of different aspects in the analysis and design of projects, as well as the amount of time necessary to complete the designs [2]. Concurrently, this leads to greater savings and reductions in costs.

Beams are critical members of civil engineering structures. Their principal function is to transmit vertical loads by means of bending action into, for example, the columns in a rectangular building frame or the abutments in a bridge which support them. Beams span between supports to carry transverse loads which are resisted by bending and shear. The compression flange of an I-beam acts like a column and will buckle sideways if the beam is not sufficiently stiff or the flange is not restrained laterally [3]. An unrestrained beam is susceptible to lateral torsional buckling. Lateral-torsional buckling (LTB) is a limit-state of structural usefulness where the deformation of a beam changes from predominantly in-plane deflection to a combination of lateral deflection and twisting while the load capacity remains first constant, before dropping off due to large deflections [4]. LTB occurs when the compression portion of a beam is no longer sufficient in strength, and instead, the beam is restrained by the tension portion of the beam which causes deflection or twisting to occur [5]. The lateral torsional behaviour of a steel beam is illustrated in Figure 1.



a) Original beam b) Laterally buckled beam

Fig. 1 Steel beam undergoing lateral-torsional buckling
(Source: Chan [6])

In the structural design of steel beams, reference to a standard/ code is essential. A standard or code serves as a reference document with relevant guidance. Today, many countries in the world have published their own codes of practice. These codes were produced through thorough research and past experiences of experts in respective fields. Some countries with no particular codes of practices adopt an established standard code as the national reference [6]. The most commonly used code of practice in Nigeria for steel design is BS 5950. Several non-European countries including South Africa, Saudi Arabia, Sri Lanka and Malaysia have based their national codes on the European standards. Eurocodes are recognized as the most advanced and completely integrated sets of structural codes which can be adjusted and modified for use in any region in the world. It is believed that Eurocode is more comprehensive and better developed compared to any other standard

[7]. In a nutshell, it is essential to study the design provisions of Eurocode 3 [8] and BS 5950 [9] in order to have an in-depth understanding of their differences.

RESEARCH OBJECTIVES

The aim of this study is to develop a computer program for the design of simply supported laterally unrestrained I-section steel beams based on the requirements of BS 5950 and Eurocode 3. The program will be developed using the C- sharp programming language. The results from the developed program will be validated using an established software-Staad-pro. The study will also review the differences in design provisions for the design of laterally unrestrained I-section steel beams based on Eurocode 3 and BS 5950. The design results of steel beams designed according to BS 5950 will be compared to Eurocode 3. The comparison will be made in terms of bending moment and shear due to design loads, beam sections and areas of the various sections obtained using the two codes.

RESEARCH METHODOLOGY

The overall process of the research and the computer program development, according to [10, 11], can be classified into the following stages

- Review of the design of laterally unrestrained beam according to the stipulations of BS 5950 and Eurocode 3
- Coding the BS 5950 and Eurocode 3 design provisions into computer algorithm using Csharp programming
- Development of the Graphical User Interface
- Testing the developed code and verification of results

The above procedure will be followed in this research. A review of the design stipulations by the relevant codes has already been carried out in the introduction section. The rest of the procedure as outlined above will now follow systematically

Design concepts of Eurocode 3 and BS 5950

EC3 is based on the limit state design which covers the ultimate limit state and serviceability state. Loadings are multiplied or divided with a given partial safety factor to ensure structures are designed with a certain degree of reliability. EC 3 complies with the principles and requirements for the safety and serviceability of structures. The basis of design and verification are given in EN 1990 [12] (Basis of structural design). Furthermore, there are two limit states concepts used in BS 5950 namely, the ultimate limit states and serviceability limit state. The partial safety factor is applied to loadings to increase the reliability of the structure.

An unrestrained beam section, according to BS 5950 and EC3, must be checked for bending resistance and lateral torsional buckling. The differences in the design provisions are outlined in Table 1.

Table 1 Beam design provisions

Eurocode 3[2005]		Elements	BS 5950[2000]	
		Partial Safety Factor for Action (Load)		
G_K = 1.35		Permanent Action (Load)	DL = 1.4	
Q_K = 1.50		Variable Action (Load)	LL = 1.6	
Flange Subject to Compression	Web Subject to Bending	Cross Section Classification	Flange Subject to Compression	Web Subject to Bending
9Ɛ	72Ɛ	*Class 1*	9Ɛ	80Ɛ
10Ɛ	83Ɛ	*Class 2*	10Ɛ	100Ɛ
14Ɛ	124Ɛ	*Class 3*	15Ɛ	120Ɛ
$\boldsymbol{\varepsilon = (275/f_y)^{0.5}}$		Coefficient, Ɛ	$\varepsilon = (275/p_y)^{0.5}$	
$\boldsymbol{V_{pl,Rd} = A_v\,(f_y/\sqrt{3})\gamma_{mo}}$		Shear capacity check	$P_v = 0.6p_yA_v$ $A_v = \text{tD}$	
$\boldsymbol{M_{pl,Rd} = W_{pl,Rd}\,f_y/\gamma_{mo}}$		Moment capacity check	$M_c = p_y\text{S}$	
$\boldsymbol{M_{b,Rd} = \chi_{LT}\,W_y\,f_y/\gamma_{m1}}$		Buckling resistance check	$M_b = \text{p}_bS_x$	

where, P_v is the shear capacity of a member. p_y is the design strength of steel. A_v is the effective shear area. D is the depth of section. t is the thickness of web. S is the plastic modulus. M_c is the plastic moment

Coding the beam design provisions

The C# programming language was used as the language to convert the EC3 and BS 5950 design provisions for unrestrained steel beam into an algorithm. Figure 2 shows the interface for the coding of the design provisions into an algorithm.

Development of graphical user interface (GUI)

A combination of programming in C# and Microsoft Visual Studio is used here to allow an artistic application to be created. Microsoft C# was chosen for this project mainly because of its advantage of presenting a visually appealing and interactive graphical user interface as well as a robust language to create code that correctly executes the desired tasks when adequately programmed. The graphical interface was created using a windows application called Windows Presentation Foundation (WPF) in visual studio.Net (Figure 3). The flowchart for the development of the program using C# programming language is illustrated in Figure 4.

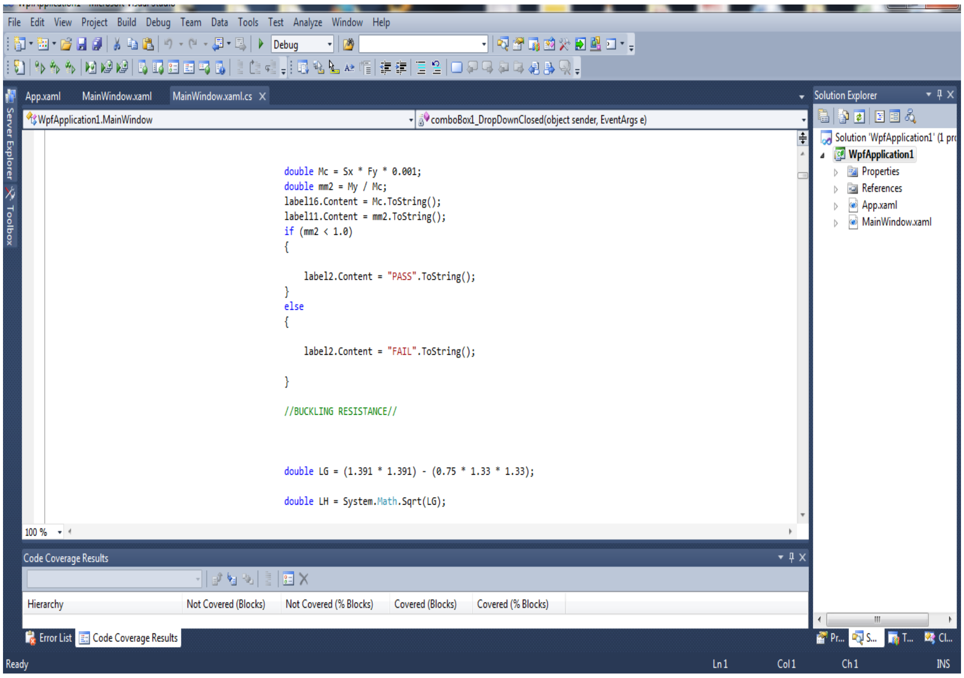


Fig. 2 Csharp coding environment

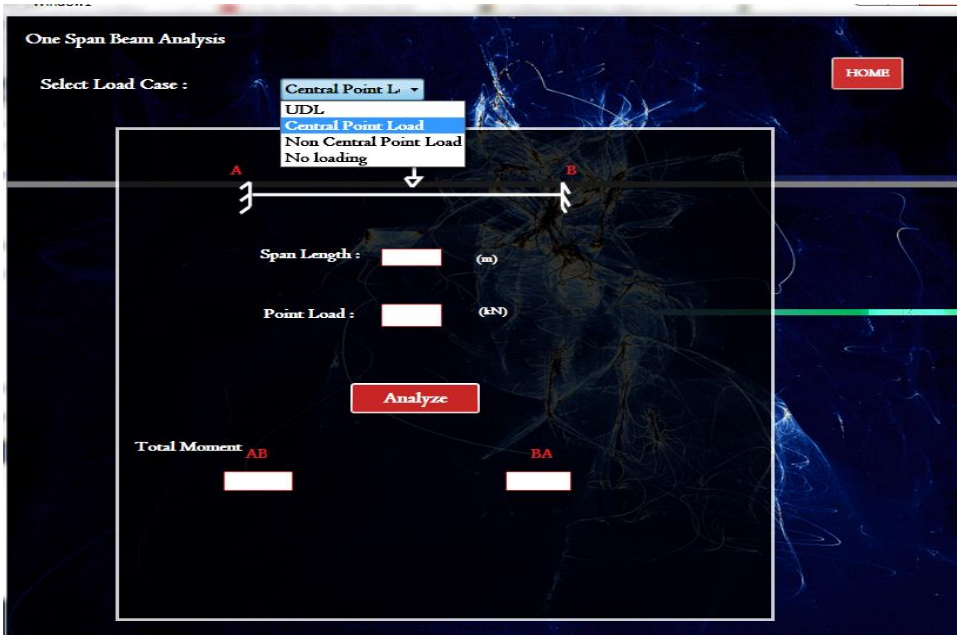


Fig. 3 Graphical User Interface of the program (analysis section)

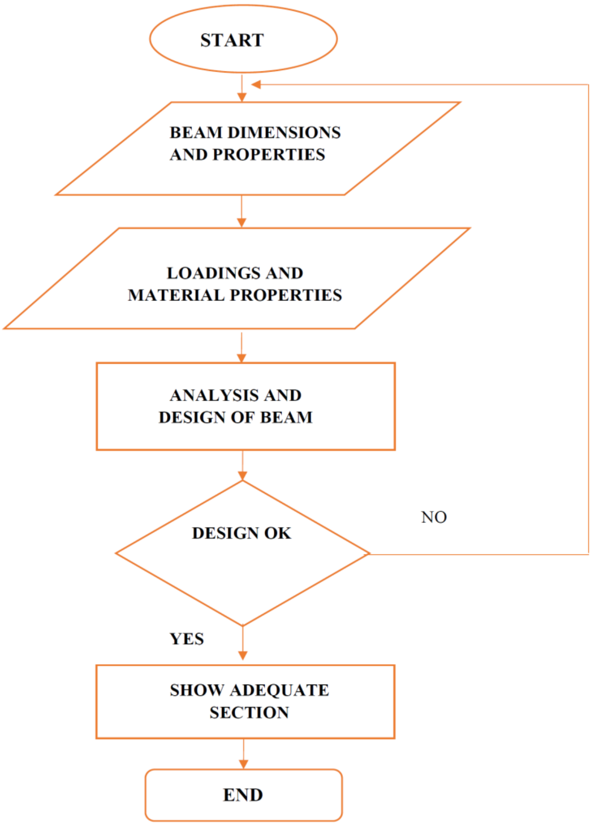


Fig. 4 Flowchart for the Development of the program using C# programming language

Testing the developed program and verification of results

A steel beam in Grade S275 was chosen for design. Several sets of simply supported laterally unrestrained beam models were designed using the developed algorithm for BS 5950 and EC3. Beam spans were varied from 2 m to 14 m at step size of 2 m and at constant values of dead (permanent) and imposed (variable) loads, the design bending moments and shears were computed. This was done in order to show the difference in the values of the bending moment and shear obtained using BS 5950 and EC3 for both the Staad.Pro software and the developed C-sharp program. The dead and imposed loads on the beams are shown in Table 2. On the basis of the bending moments and shears obtained, design was carried out according to both codes using each of Staad.Pro and the developed C-sharp program and adequate beam sections were selected. The design carried out using the Staad Pro software application was used to validate the design results obtained using the developed program.

Table 2 Beam loadings

Load Contributor	Dead Load	Live Load
Load (kN/m)	45	55

Other relevant information includes the following: Young Modulus, E = 210 GPa. Steel Grade, P_y = S275 N/mm^2

RESULTS AND DISCUSSION

Several sets of beam geometries were set to compare the design results of the beams designed according to BS 5950 and EC 3.

Beam design bending moment and shear

The design moment and shear of the beams at varying span length were compared and tabulated as shown in Tables 2 and 3 respectively. The tables reveal that an increase in span length for the test cases translates to an increase in the bending moment and shear. A similar trend was observed in the developed program and Staad Pro. Generally, from Table 4, the calculation based on EC3 had reduced member design shear compared to BS 5950. This can be attributed to the different shear design formulations specified by both codes.

Table 3 Comparison of Beam design bending moment at varying span length

Beam No.	Span Length (m)	Developed Program		Staad-Pro	
		BS 5950 (kNm)	EC 3 (kNm)	BS 5950 (kNm)	EC 3 (kNm)
I2A	2	132	97	131.81	97.08
I4B	4	246	181	243.50	181.23
I6C	6	333	246	332.23	246.4
I8D	8	431	353	431.22	353.93
I10E	10	533	404	533.75	404.53
I12F	12	591	479	591.56	479.92
I14G	14	869	764	869.53	764.90

Table 4 Comparison of beam design shear at varying span length

Beam No.	Developed Program		Staad-Pro	
	BS 5950 (kN)	EC 3 (kN)	BS 5950 (kN)	EC 3 (kN)
I2A	266	246	262.41	245.12
I4B	434	421	435.50	425
I6C	546	477	540.30	479.34
I8D	679	651	671.74	655.41
I10E	774	676	778.44	677.42
I12F	847	797	845.53	798.22
I14G	1072	942	1068.22	943.12

Beam Cross-sectional area

The optimum sections identified for each beam and the cross-sectional area of beams at varying span length are the same using Staad- Pro and the developed program. The optimum design sections obtained, and the area of sections are presented in Table 5 and 5 respectively. The percentage difference between the results was calculated as Equation 1, and the results are shown in Table 6.

$$\% \, difference = \frac{|Result \; for \; BS \; 5950 - Result \; for \; EC \; 3|}{Result \; for \; BS \; 5950} \times 100 \, \% \qquad (1)$$

Tables 5 indicate that the comparison of BS 5950 design results and EC 3 design results gave an average difference of 21.5 % for the area of sections obtained. This shows that beams designed using the requirements of EC 3 are economical. Close examination of Table 5 reveals that the area of the beam section (and by extension, the weight of the beam also) increases as the span length increases. This shows that the longer the span, the greater the weight of the beams.

Table 5 Comparison of beam design section sizes at varying span lengths using the developed program and Staad Pro.

Beam No.	Span length (m)	Developed program		Staad Pro	
		BS 5950 (Section)	EC3 (Section)	BS 5950 (Section)	EC3 (Section)
I2A	2	254 × 146 × 37	254 × 102 × 28	254 × 146 × 37	254 × 102 × 28
I4B	4	356 × 171 × 51	356 × 127 × 39	356 × 171 × 51	356 × 127 × 39
I6C	6	356 × 171 × 67	356 × 171 × 51	356 × 171 × 67	356 × 171 × 51
I8D	8	457 × 191 × 74	457 × 152 × 60	457 × 191 × 74	457 × 152 × 60
I10E	10	457 × 191 × 89	457 × 191 × 67	457 × 191 × 89	457 × 191 × 67
I12F	12	457 × 191 × 98	457 x 191 × 82	457 × 191 × 98	457 × 191 × 82
I14G	14	610 x 229 × 113	533 x 210 × 92	610 x 229 × 113	533 × 210 × 92

Table 6 Comparison of the area of sections for the beams at varying span length using the developed program and Staad Pro

Beam No.	Span Length (m)	Developed program			Staad Pro		
		BS 5950 (m^2)	EC 3 (m^2)	% Difference	BS 5950 (m^2)	EC 3 (m^2)	% Difference
I2A	2	47.2	36.1	23.5	47.2	36.1	23.5
I4B	4	64.9	49.8	23.3	64.9	49.8	23.3
I6C	6	85.5	64.9	24.1	85.5	64.9	24.1
I8D	8	94.6	76.2	19.5	94.6	76.2	19.5
I10E	10	114	85.6	24.9	114	85.6	24.9
I12F	12	125	104	16.8	125	104	16.8
I14G	14	144	117	18.8	144	117	18.8
			Average	21.5%		Average	21.5%

Beam buckling capacity

The buckling capacity of a specific beam Test Section (Beam designation I2A) with design section 254 × 146 × 37 (Table 5) and constant beam loadings (Table 2) was evaluated at varying laterally unrestrained span lengths. The obtained buckling capacities are presented in Table 7. The elastic critical moment for lateral-torsional buckling is calculated according to EC 3 [8] and BS 5950 [9] procedures. From the table, it was observed that the buckling capacity decreases considerably for both BS 5950 and EC 3 as the length of the span increases. A similar result was obtained using the developed program and Staad-Pro. It is logical to conclude that the longer the unrestrained length of the beam, the more it is susceptible to lateral torsional buckling. From Table 7, the lateral torsional buckling moment resistance values are smaller for EC3 than those of the BS 5950. In other words, using EC3 is more economical than BS 5950. One of the reasons why these results are different for both code of practice is because of the lower value of partial factor for both the imposed and the dead loads for EC3 compared to the BS 5950.

Table 7 Comparison of buckling capacity beam I2A at varying span length

Design Section	Span Length (m)	BS 5950 (kNm)	EC 3 (kNm)
254 × 146 × 37	2	104.6	102.3
254 × 146 × 37	4	66.96	62.9
254 × 146 × 37	6	47.37	46.3
254 × 146 × 37	8	36.65	32
254 × 146 × 37	10	29.99	28

CONCLUSION

A simple task-specific computer program for the design of I-section steel beams susceptible to lateral torsional buckling using the requirements of Eurocode 3 and BS 5950 has been developed. The program was developed using the Microsoft C-sharp programming language. The design results obtained using the developed program were similar to the results obtained using the established standard software Staad-Pro. Besides, this research has established the similarities and differences in the design provisions of Eurocode 3 and BS 5950. For a specific beam section with constant loadings, as the span length increases the buckling capacity reduces, thus the longer the beam, the more it is susceptible to lateral torsional buckling. The comparison of BS 5950 design results and EC 3 design results gave an average difference of 21.5 % for the area of sections obtained in favour of EC3 procedure. For instance, for a 10 m long beam, with grade S275, designed using BS 5950 requirements, the area of section obtained is 144 m^2 whereas an area of section of 85.6 m^2 was obtained for the same beam designed using the requirements of EC 3. This shows that the beam designed using the requirements of EC 3 is more economical. There is a slight difference in terms of the design process between EC3 and BS 5950.

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RAZVOJ KOMPJUTERSKOG PROGRAMA ZA PROJEKTOVANJE ČELIČNIH NOSAČA SLOBODNIH NA OBA KRAJA

Ovi istraživanje predstavlja rezultate korišćenja kompjuterskog programa koji se zasniva na C-sharp softveru, razvijenom u cilju projektovanja čeličnih nosača I profila slobodno oslonjenih na oba kraja. Program je razvijen na osnovu onoga što propisuju BS 5950 i Eurocode 3 (EC3) standardi projektovanja.Korišćenjem razvijenog programa, projektovano je nekoliko grupa modela čeličnih nosača sa istim dimenzijama poprečnog preseka ali sa različitim rasponima, slobodno oslonjenih na oba kraja. Rezultati su provereni korišćenjem postojećeg programa, Staad Pro. Došlo se do saznanja da su dobijeni rezultati projektovanja slični onima koji su dobijeni korišćenjem Staad Pro softvera. Kod specificiranih preseka nosača pri konstantnim opterećenjima, povećanje raspona slobodno oslonjenih greda na oba kraja smanjuje čvrstoću na savijanje, tako da što je duži nosač, to je osetljiviji na bočno torziono izvijanje. Poređenje rezultata dobijenih korišćenjem BS 5950 sa onima dobijenih korišćenjem EC 3 različitih dužina raspona nosača slobodnih na oba kraja otkriva da su vrednosti dobijene korišćenjem BS 5950 u proseku 21.5%, više od onih dobijenih korišćenjem EC3. Stoga su nosači sa bočno neukliještenim pritisnutim flanšama projektovani u skladu sa zahtevima EC 3 ekonomičniji. Razlika u rezultatima dolazi od razlika u principima projektovanja i merama korišćenjim u ova dva standarda.

Ključne reči: *grede slobodno oslonjene na oba kraja, Eurokod 3, BS 950, C-Sharp, bočno torziono savijanje*