Reliability - Based Sensitivity Assessment of Design Parameters for Steel Section Members under Compression and Bending

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Abstract

The sensitivity of design parameters for members subjected to axial compression and bending stresses were assessed using linear fitting of the sensitivity curves. Design loadings were obtained from an analysis of idealized five - story steel structure and EC3 design provisions were used to design members of the framed structure. First Order Reliability Method (FORM) coded in FORM5 was used for the reliability analysis and values of the design parameters were varied from -15% to 15% at an interval of 5%. The result of the linear fits provides a satisfactory representation of the curves from which the coefficient of sensitivity for each design parameter was obtained. The result showed that yield strength is the most sensitive parameter with an average degree of sensitivity (DOS) of 27^0. At lower axial stress the plastic section modulus (Zp) is second most sensitive with DOS of 15^0 and cross sectional area (A) is the least sensitive with 13^0. At higher axial stresses, cross sectional area is second to yield strength with 15^0 while plastic section modulus is the least sensitive with 13^0. The result of the study also shows that members under a combination of low axial stress and high bending moment and also high axial stress and high bending moment result in low structural safety of a member. The study therefore recommends that for design of members under low axial stress and higher bending moment, sections with higher plastic section modulus. For members under high axial stress and bending moment, sections with high cross sectional area as well as high plastic section modulus are recommend for their design.

***Keywords*:** Bending, Compression, Reliability, Sensitivity, Steel

1 INTRODUCTION

IMPERFECTIONS during fabrication of steel sections in steel factories and also during construction of steel structures usually result in weakness in the strength capacity of the steel section. Some members that are design to carry only compressive load are being transformed to carry in addition, bending loads due eccentricity. Furthermore, the study uses code equations in the analysis because the current generation of structures are design based on codified procedures which make it necessary to carry out sensitivity analysis of the parameters for the purpose of reviewing and improving the design equations. Quantification of the significance of the design parameters which form part of this paper will be very important in reviewing and improving member design equations.

In recent years more attention was given to the area of sensitivity analyses by researchers such as the work by Li (2019), Moradi et al. (2019), Kala and Valves, (2018) etc. Li (2019) use sensitivity analysis to detect damage in beam-column rotation angles with respect to linear stiffness of the frame of the structure. Dukes et al. (2012) conducted a sensitivity study to test which design parameters have a significant impact on bridge response and should therefore be considered as a predictive variable in bridge specific fragility analysis used in the design process. Five design parameters which are Design axial load (N_{ED}), Design bending moment in major axis and minor axis (M_{ED}), yield strength of section (f_y), Plastic section modulus of the section (W_{pl}) and Cross-sectional area of the section (A) were used for the study and all of them were shown to contribute significantly to the prediction of component responses.

Liu and Song (2014) studied and discussed the reliability of a portal frame based on space overall ultimate bearing capacity, gets the range of the structural reliability indices and the sensitive degree of each parameter on the reliability, and presents the measures to improve reliability.

Kim, et al. (2011), investigated the sensitivity of design variables of steel buildings subjected to progressive collapse. The results showed beam yield strength as the most significant design parameter in the dual system buildings.

2 METHODOLOGY

2.1 Model Framed Structure

An idealized five - story steel framed structure consisting of concrete panels was used for this study (Figures 1a and 1b)

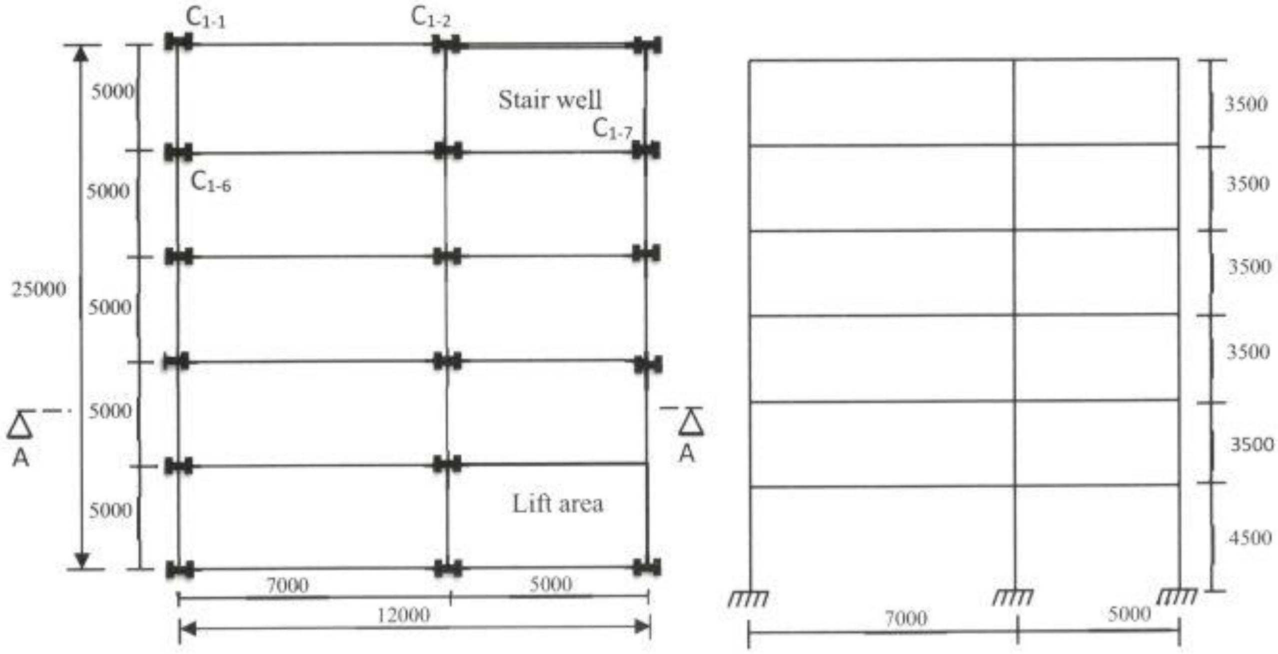

Figure 1a: Plan view of the steel frame *Figure 1b: Section A-A*

***Figure 1.** An idealized five - story steel framed structure*

The frame consists of six floors and two bays. The members of the frame consist of universal beam (UB) sections and universal column sections (UC) and all the joints of the frame are considered fixed. The frame is subjected to three basic load cases, which are dead, live and wind loads respectively. Design loadings were obtained considering public usage of the steel frame and analysis of the frame was carried out to determine member loadings and a mini program was developed using Microsoft excel to facilitate the design of members using EC3 (2003) for the limit state of flexural buckling. The members of the frame together with the loadings are presented in Table1. Columns on the ground floor, first floor and second floor are considered as C_1, C_2 and C_3 respectively. This means that C_{1-1} refers to column number one on first floor, C_{2-4} is column number four on second floor, and C_{3-5} is column number five on third floor and so on. The ground floor is considered as the first floor. Some of the column members are design twice with different sections to have varying axial stresses for the study.

Table 1: Loadings on Column Members

Member	N_{ED}	M_{xED}	M_{zED}
C_{1-1}	1035	291	23.0
C_{1-2}	1255	399	21.0
C_{1-6}	1405	345	12.0
C_{1-7}	2148	269	0.2
C_{1-13}	2189	268	2.2
C_{2-8}	3159	365	2.0
C_{3-5}	1949	312	16.8
C_{3-8}	2366	291	1.6
C_{4-8}	1555	212	1.4

Members subjected to compression and bending (EC 3 Design provisions)

The study considers the limit state of flexural buckling (doubly-symmetric cross-section): (EC3 5.5.1, (2003) as shown in the interactive Eq. (1)).

$$\frac{N_{Ed}}{\chi_y.N_{RK}/\gamma_{M1}} + K_{yy}\frac{M_{y.Ed} + \Delta M_{y.Ed}}{\chi_{LT}.M_{y.Rk}/\gamma_{M1}} + K_{yz}\frac{M_{z.Ed} + \Delta M_{z.Ed}}{M_{z.Rk}/\gamma_{M1}} \leq 1.0 \quad ------ \quad (1)$$

K_{yy} and k_{yz} are interaction factors, values are obtained from Annex A in EN 1993-1-1

$$\Delta M_{yEd} = \Delta M_{zEd} = 0, \text{for class 1, 2 and 3 cross sections}$$

Based on load requirement a typical section 356x356x202 UC was used to design the column members of the model frame. The analysis is conducted in order to study the sensitivity of the design parameters as the axial stress in the member. All the members used for the study have satisfied the codes safety criteria (i.e. not exceeding the unity value). Members considered for this study fall under class 1 and 2 cross- section.

2.2 Reliability Analysis

First Order Reliability Method (FORM) coded in FORM5 (Gollwitzer et al., 1988) was used for the reliability analysis. Values of the design parameters were varied from -15% to 15% and reliability analyses ran to obtain reliability index corresponding to each varied value. The random variables were obtained from 5.5.1 of EC3 and they are design axial force (N_{ED}), design moment in the major axis (M_{yED}), design moment in the minor axis (M_{zED}), Cross sectional area of the section (A), yield strength of the section (f_y), plastic section modulus of the section in major axis ($W_{pl,y}$) and plastic section modulus of the section in minor axis ($W_{pl,z}$). The statistical properties of the random variables are presented in Table 2.

Table 2: Statistical properties for random variables

Variable	Mean Coefficient	COV	Distribution Type
N	1.0	0.05	Normal*
M	1.0	0.1	Lognormal*
A	1.0	0.05	Lognormal*
f_y	1.0	0.07	Lognormal*
W_{pl}	1.0	0.07	Normal**

* (JCSS, 2000)

** (Ellingwood, 1983)

The limit state equation for flexural buckling derived from equation 5.5.1 EC3 is expressed in Eq. (2).

$$G(N_{ED}, M_{yED}, M_{zED}, A, f_y, W_{pl}) = (N_{ED}A^{-1}f_y^{-1}) + (M_{yED}W_{pl.y}^{-1}f_y^{-1}) + (M_{zED}W_{pl.z}^{-1}f_y^{-1}) - 1 = 0 --- (2)$$

2.3 Sensitivity Analysis

Charts were plotted to obtain the curves of reliability indices against per cent variation of values of design parameters. Linear fittings of these curves were made to obtain sensitivity coefficients of the design parameter.

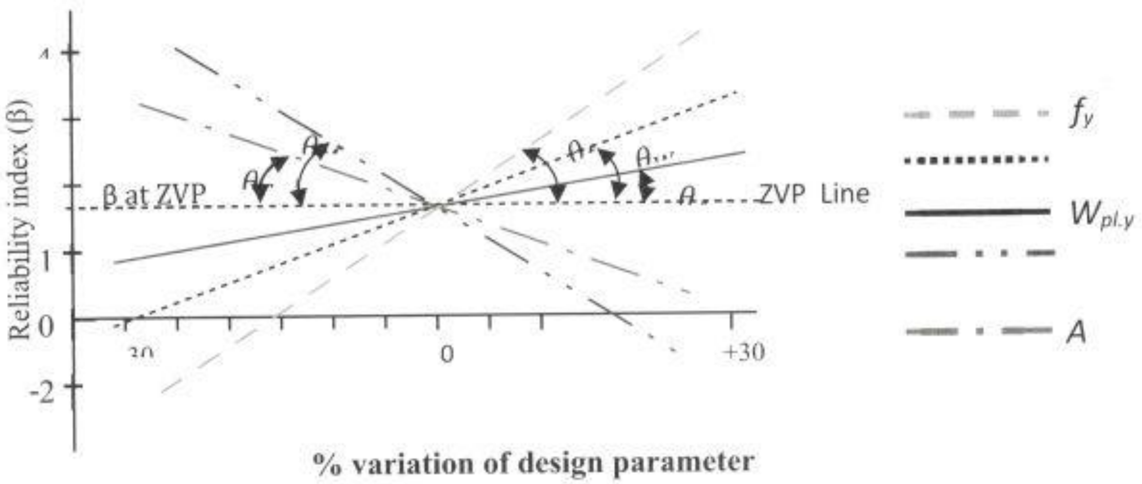

Figure 2: A typical Sensitivity chart

The coefficients of sensitivity were used to obtain the angle between the curve for the varied values of the parameter and line corresponding to zero variation of the parameter (ZVP) (Figure 2). This angle represents the deviation of the curve of reliability index (due to variation of the value of the parameter) from the reliability index line corresponding to ZVP. These angles are referred to as the degree of sensitivities of the parameters and are used to rank the sensitivity of the parameters.

3.0 RESULTS AND DISCUSSION

Figure 3 presents the variation of reliability index and unity value under varying axial stress and bending moment.

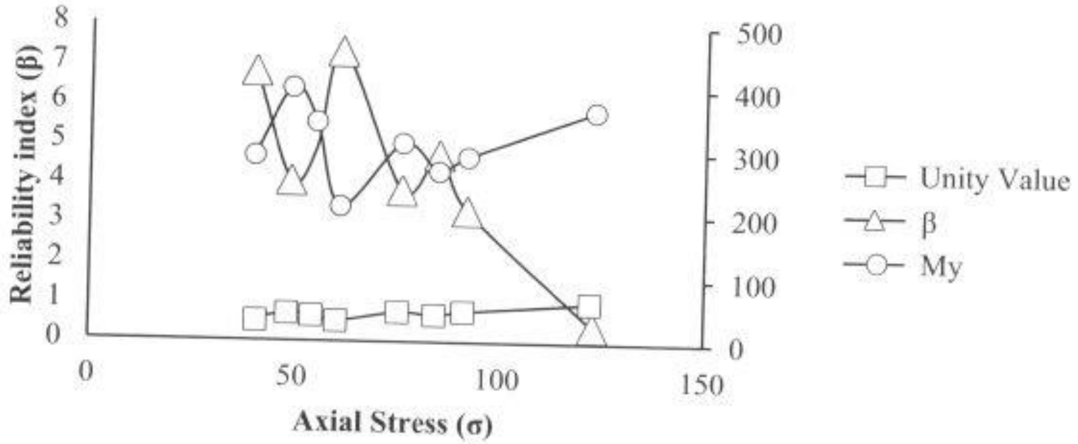

Figure 3: Variation of Reliability index (β) and Unity value under varying Axial stress (σ) and Bending Moment (M)

Figure 3 showed that variability of the axial stress and bending moment greatly affects the unity value and reliability index. As the axial stress and bending moment increase the reliability index decrease while the unity value increase. Points of higher bending moment were seen to have higher unity values and low reliability indices. The figure also showed that bending moment has significant effect on the unity value and reliability index when combined with axial stress. A combination of low axial stress with high bending moment results in high unity value and low reliability index. A worse and undesirable combination is higher axial stress combine with higher bending moment as seen on the chart.

Figure 4 displays the combine effect of axial stress and bending moment on the angle of deviation for yield strength curve.

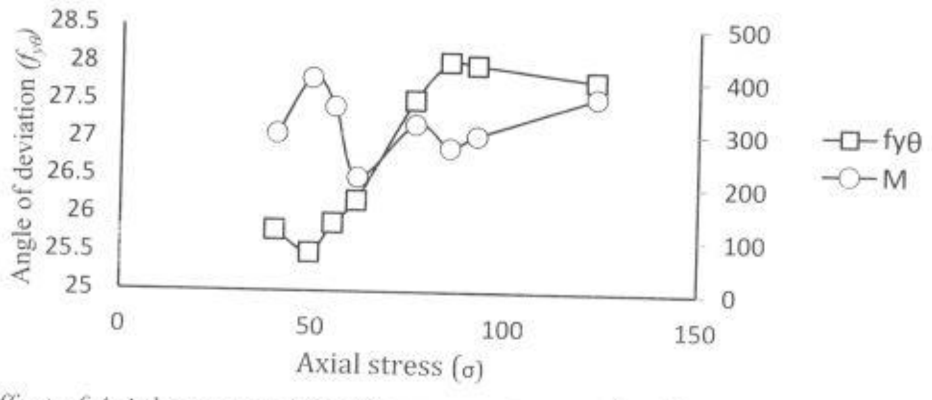

Figure 4 : *Effect of Axial stress and bending moment on angle of deviation for f_y*

The chart shows that the bending moment affects the angle of deviation more at low axial stress by reducing the angle of deviation. High bending moment combine with low axial stress results in reducing the angle of deviation. At high axial stress the effect of the bending moment on the angle of deviation is significantly very low. Low bending moment combine with high axial stress result in increase in angle of deviation.

Figures 5 – 12 present's variation of reliability index with percentage variation of parameter values for individual members of the steel frame used for the study. In all the Figures the yield strength curve shows more deviation from the reliability index line at zero variation of parameter (RILZVP) signifying a higher coefficient of sensitivity and a much bigger angle of deviation from RILZVP. The angle of deviation of the parameter is measured from the RILZVP to the parameter curve in anti-clockwise direction. The point of convergence of the curves represents the reliability index of the design at zero variation of the parameters.

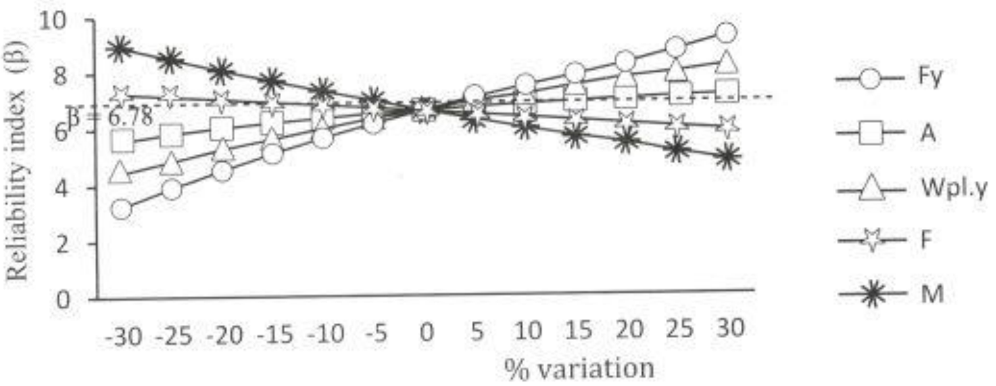

Figure 5: Variation of Reliability index β on C_{1-1} with 356X368X202UC ($\sigma = 40N/mm^2$)

Figure 5 presents the result of the reliability and sensitivity analysis for member one on the first floor. The loading on the member are as presented in Table 2. The member is under an axial stress of $40N/mm^2$ which is a relatively low stress condition. The figure showed that after the yield strength curve, the plastic section modulus curve shows more deviation from RILZVP among resistance parameters. It has an angle of deviation higher than that of cross-sectional area (Tables 3). Among load parameters the figure showed bending moment curve having more deviation than the axial force curve. The design has a reliability index of about 6.78.

Table 3: Linear Fit Result for Member C_{1-1}

Parameter	Coefficient of Sensitivity	Linear fitness R^2 (%)	Θ (degree)
f_y	0.4826	99.3	25.8
W_{pl}	0.3109	99.0	17.3
A	0.1250	96.1	7.1
F	0.1152	99.9	6.6
M	0.3401	99.5	18. 8

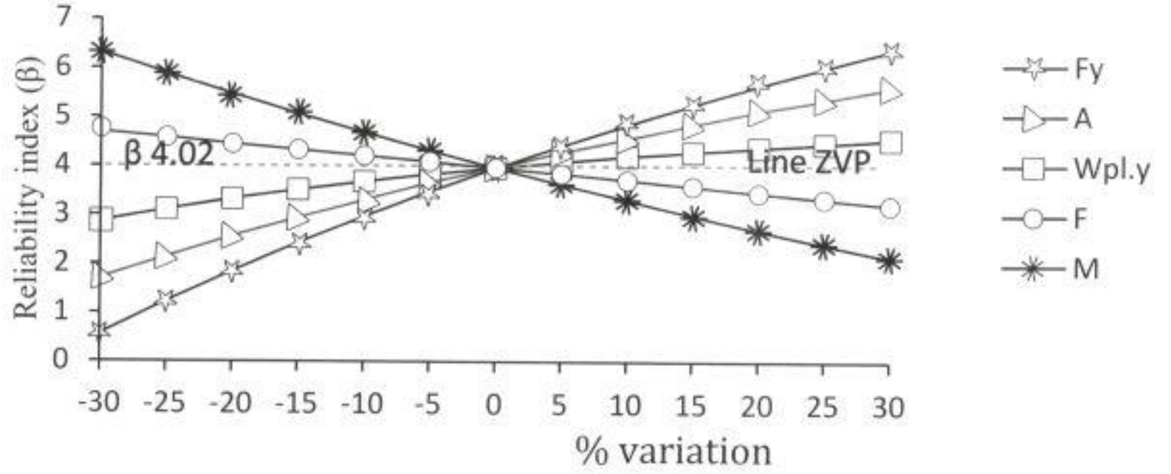

Figure 6: Variation of Reliability index β on C_{1-2} with 356x368X202UC (σ= 49N/mm²)

Figure 6 present the result for second member on the first floor C_{1-2}. The result is virtually the same as the result for member C_{1-1} in Figure 5. Here the angle of deviation of the yield strength curve has reduced from 25.80 to 25.50 as presented in Table 4 this is because the bending moment acting on member C_{1-2} is higher than the moment acting on member C_{1-1}. As elaborated in Figure 4 low axial stress combine with high bending moment result in reduction of the angle of deviation of the yield strength curve.

Table 4: Linear Fit Result for Member C_{1-2}

Parameter	*Coefficient of Sensitivity*	*Linear fitness R^2 (%)*	*Θ (degree)*
f_y	0.4772	99.1	25.51
W_{pl}	0.3203	99.1	17.76
A	0.1341	96.8	7.64
F	0.1250	100	7.13
M	0.3482	99.5	19.20

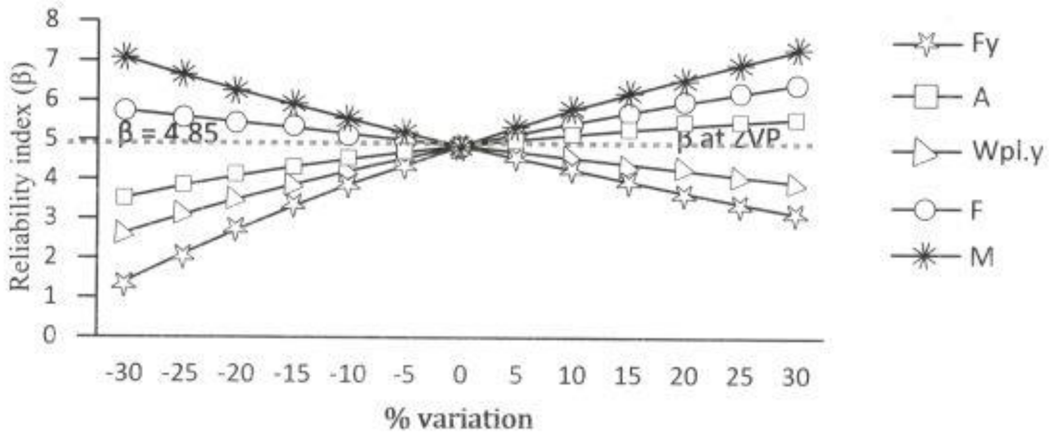

Figure 7: Variation of Reliability index β on C_{1-6} with 356X368X202UC (σ = 55N/mm²)

The deviation of the curves in Figure 7 follows the same ranking as in Figures 5 and 6. The member is under an axial stress of 55N/mm^2 which is higher than that of the member in Figure 6 and the angles of deviation are a little higher than the angles in Figures 5 and 6. The design reliability index at zero variation of parameter (ZVP) is about 4.85 which are higher than that in Figure 6. Though the axial stress on the member here is higher than that on member C_{1-2} in Figure 6 but the bending moment on the member here is less as seen in Table 2. This makes the reliability index to rise above that in Figure 6.

Table 5: Linear Fit Result for Member C_{1-6}

Parameter	*Coefficient of Sensitivity*	*Linear fitness R^2 (%)*	*Θ (degree)*
f_y	0.4846	98.9	25.9
W_{pl}	0.3112	99.0	17.3
A	0.1635	96.7	9.3
F	0.1525	99.9	8.7
M	0.3267	99.5	18.1

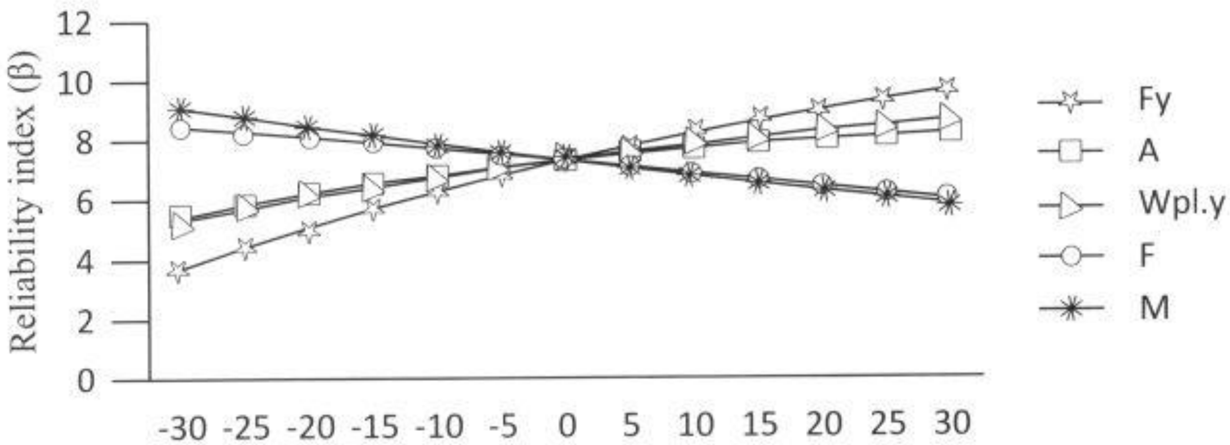

Figure 8: Variation of Reliability index β on C_{4-8} with 356x368X202UC (σ= 61N/mm^2)

In Figure 8 the behaviors of the curves remain the same and the reliability index is 7.3 which is high since the bending moment on this member is less than that in Figures 6 – 8. The axial stress on this member combine with the bending moment on the member gives rise to 26.20 (Table 6) angle of deviation for the yield strength curve. The sensitivity ranking of the parameters remains the same as in the previous charts.

Table 6: Linear Fit Result for Member C_{4-8}

Parameter	Coefficient of Sensitivity	Linear fitness R^2 (%)	Θ (degree)
f_y	0.4917	98.7	26.2
W_{pl}	0.2767	98.8	15.5
A	0.2281	96.2	12.9
F	0.2081	99.8	11.8
M	0.2726	99.75	15.3

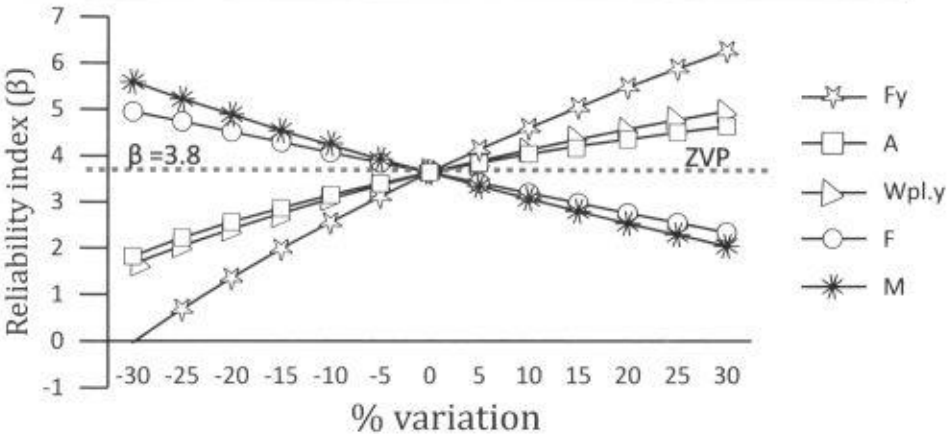

Figure 9: Variation of Reliability index β on C_{3-5} with 356x368x202 (σ =76N/mm²)

The behavior of the curves observed in Figure 9 is the same as in the previous charts. The reliability index is 3.8 which is low compared to the previous charts and this is because the bending moment is high combined with relatively high axial stress. The combination gives rise to 27.50 (Table 7) angle of deviation for the yield strength curve.

Table 7: Linear Fit Result for Member C_{3-5}

Parameter	Coefficient of Sensitivity	Linear fitness R^2 (%)	Θ (degree)
f_y	0.5212	99.2	27.53
W_{pl}	0.2747	98.8	15.36
A	0.2306	97.4	12.99
F	0.2177	100	12.28
M	0.2932	99.7	16.34

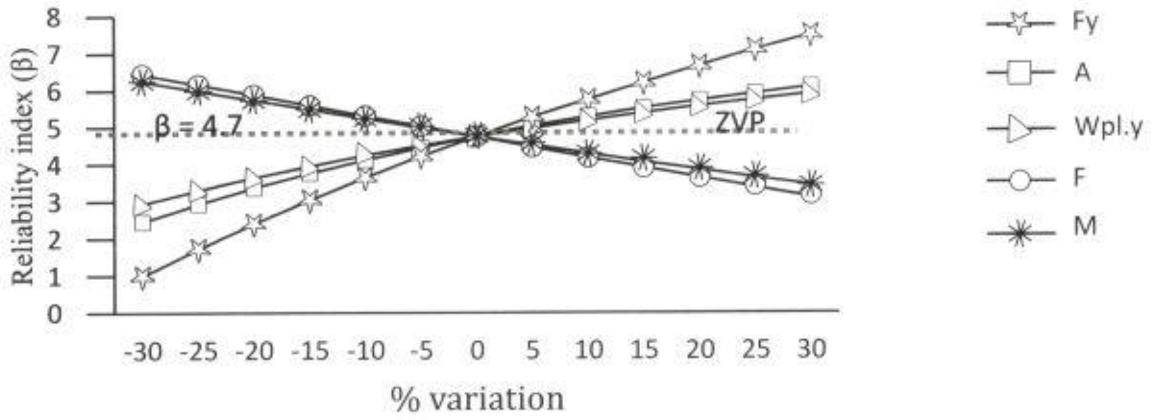

Figure 10: Variation of Reliability index β on $C_{1\text{-}13}$ with 356x368x202UC (σ = 85N/mm²)

In Figure 10 where the member is under an axial stress of 85N/mm² marks a turning point in hierarchy of deviation between plastic section modulus curve and cross-sectional area curve and also between bending moment curve and axial force curve among resistance and load parameters respectively.

Table 8: Linear Fit Result for Member $C_{1\text{-}13}$

Parameter	Coefficient of Sensitivity	Linear fitness R^2 (%)	Θ, (degree)
f_y	0.5327	99.2	28.04
W_{pl}	0.2409	98.4	13.54
A	0.2953	97.8	16.45
F	0.2799	100	15.64
M	0.2364	99.9	13.30

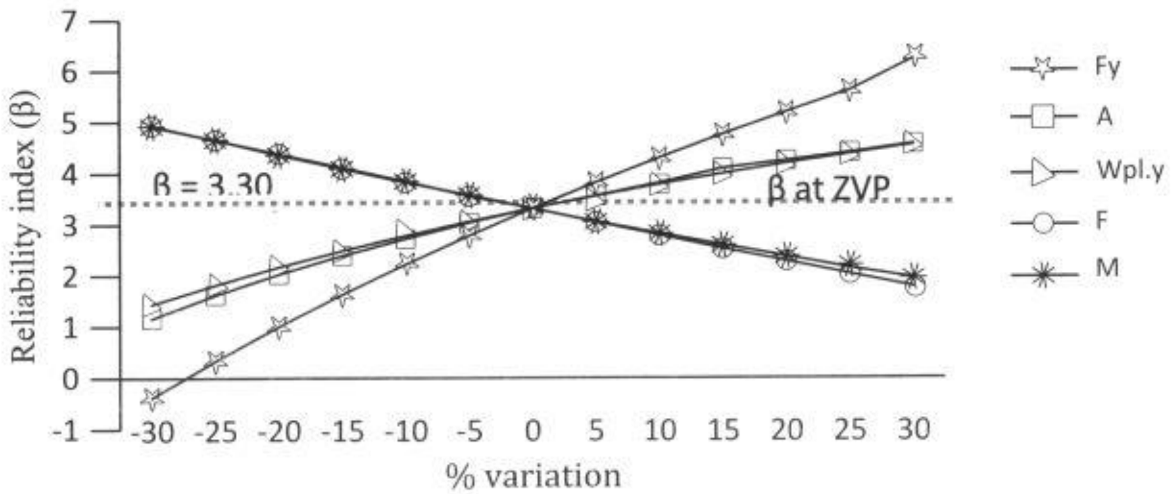

Figure 11: Variation of Reliability index β on $C_{3\text{-}8}$ with 356X368X202UC (σ = 92N/mm²)

Table 9: Linear Fit Result for Member C_{3-8}

Parameter	Coefficient of Sensitivity	Linear fitness R^2 (%)	Θ(degree)
f_y	0.5325	99.4	28.0
W_{pl}	0.2540	98.6	14.3
A	0.2786	97.7	15.6
F	0.2631	99.9	14.7
M	0.2498	99.7	14.0

In Figure 11 the same observation is made as in Figure 10 where a change of hierarchy has taken between plastic section modulus curve and cross-sectional area curve and also between bending moment curve and axial force curve among resistance and load parameters respectively.

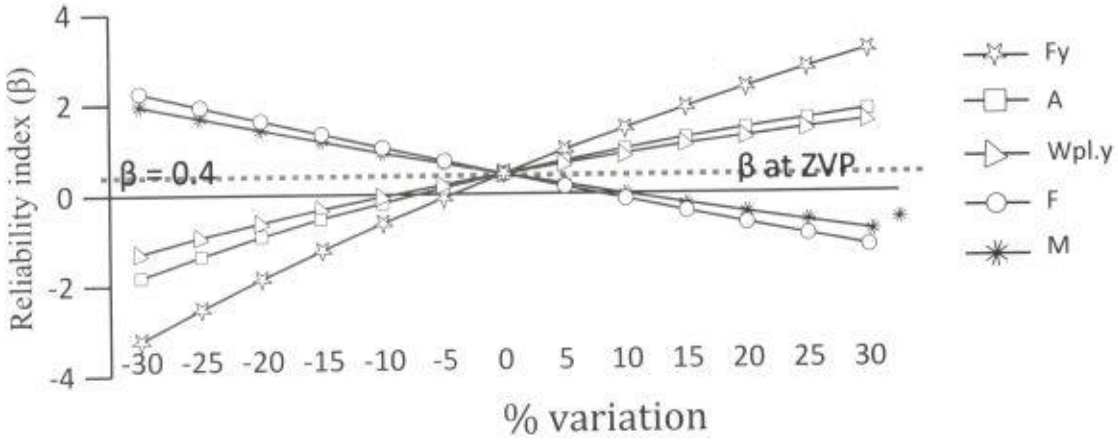

Figure 12: Variation of Reliability index β on C_{2-8} with 356X368X202UC (σ =123N/mm²)

In Figure 12 it is clear that the angle of deviation for cross – sectional area curve (16.60) has now exceeded the angle of deviation for plastic section modulus curve (13.20) and also the angle for axial force curve (160) has also exceeded the angle for bending moment curve (13.20). The graph shows that at higher axial stress condition the cross sectional area is more relevant in the design than plastic section modulus. A combination of high axial stress and bending moment is seen here given rise to low reliability index of 0.44. The result indicates clearly that yield strength is the most sensitive parameter with an average degree of sensitivity (DOS) of 27° (Tables 3 - 9). At low axial stress condition, the plastic section modulus is the second most sensitive with an average DOS of 17° while cross section area is the least sensitive with an average DOS of 8° among resistance parameters. At higher axial stresses cross sectional area takes the second position with average DOS of 16° while plastic section modulus is the least sensitive with 14°. Among the load parameters the bending moment is the most sensitive under low axial stress with 18° while axial load F is the most sensitive under higher axial stresses with 15°.

4. CONCLUSION

From the result of this study it is concluded that yield strength (f_y) is the most critical parameter in the design of members subjected to combine compression and bending and its variability will significantly affect the safety of the members. Also for members subjected to higher bending relative to compression, sections with higher plastic section modulus will be more adequate. Similarly members subjected to higher compression relative to bending, sections with high cross sectional areas will be more adequate. The result of the study also shows that members under a combination of low axial stress and high bending moment and also high axial stress and high bending moment result in low structural safety of a member.

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