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Proceeding Paper

Behaviour of Concrete Column Reinforced with Steel Bars Exhibiting Uncertain Yield Strength †

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Abstract: In Pakistan, raw material from several sources is utilized in the production of steel bars; consequently, the chemical and mechanical properties of locally manufactured bars differ drastically. According to the reviewed literature, there is a significant amount of variation in the data on rebar yield strength. This unintentionally higher yield strength might have serious consequences on a reinforced concrete (RC) column, as the failure mode could shift from ductile to brittle. The purpose of this study is to investigate the repercussions of an unintentionally higher rebar yield strength on an RC column. In order to mitigate the effects of an unintentionally higher rebar yield strength on the behaviour of the RC column, some modifications to the design approach are recommended.

Keywords: uncertain yield strength; higher yield strength; RC column; production flaws; RC design; failure mode

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1. Introduction

Unmonitored and unmanaged construction is relatively common in Pakistan since the construction industry is not scientifically organised [1]. Materials having unknown characteristics are frequently utilised. Considering that several parts of Pakistan are in seismically active zones, safety should be the top consideration. Even though ACI guidelines are employed by designers, the capacity of structural members to withstand axial and seismic loads is uncertain since the local construction industry uses low-cost steel having uncertain properties to minimize costs; as a result, a major devastation might occur during a seismic event.

The present seismic design philosophy of RC structures is primarily dependent on the ductility and energy absorption capability of steel; hence, steel bar quality must be maintained [2]. Lodi and Masroor [3] reported that raw materials from many sources are utilised in the production of steel bars; consequently, the chemical and mechanical properties of locally manufactured bars differ drastically. Rafi et al. [4] investigated the chemical and mechanical properties of locally manufactured steel bars. It was found that the bars' chemical composition fulfilled the criteria of ASTM A615 [5], but a large proportion of them failed to achieve the specified strength and elongation requirements. The yield strength criteria of the standards were not met by 13% of the tested hot-rolled deformed bars. A considerable proportion of cold-twisted ribbed bars (33%) exhibited a yield strength that was lower than that required. Furthermore, a considerable dispersion in the strength data was observed, which exceeded the ASTM A615 recommendation. The yield and ultimate tensile strengths of rebars were found to vary by more than 70% from the specified value in the standard. The design implications of employing these bars were also investigated, and it was determined that the failure mode of flexural members might shift from ductile to brittle. Manzoor and Ahmad [6] conducted a study on Grade 420 and

Grade 500 rebars in Pakistan. The results demonstrated that 50% of the Grade 500 bars did not meet the specified minimum strength. The average yield strength of the sample rebars for Grade 420 rebars was 540 MPa, which was greater than the specified yield strength of 420 MPa.

Based on the examined literature, it is logical to argue that due to production flaws, bars manufactured in Pakistan exhibit an unintentional higher yield strength than that specified by ASTM A615. This unintentional higher yield strength could have serious implications on the design of flexure and compression members. The purpose of this study is to investigate the implications of an unintentionally higher rebar yield strength on an RC column design. Certain changes to the design procedure are recommended to mitigate the consequences of an unintentionally higher rebar yield strength on the behaviour of an RC column.

2. Methodology

A sectional analysis of an RC column was conducted employing spreadsheets and a MATLAB (MathWorks, Natick, MA, USA) script to plot axial and biaxial load–moment interaction diagrams. A comprehensive parametric study was conducted to investigate the effect of a higher yield strength on an RC column. The parameters of analysis included column cross section, steel ratio, steel yield strength, and concrete compressive strength, as shown in Figure 1.

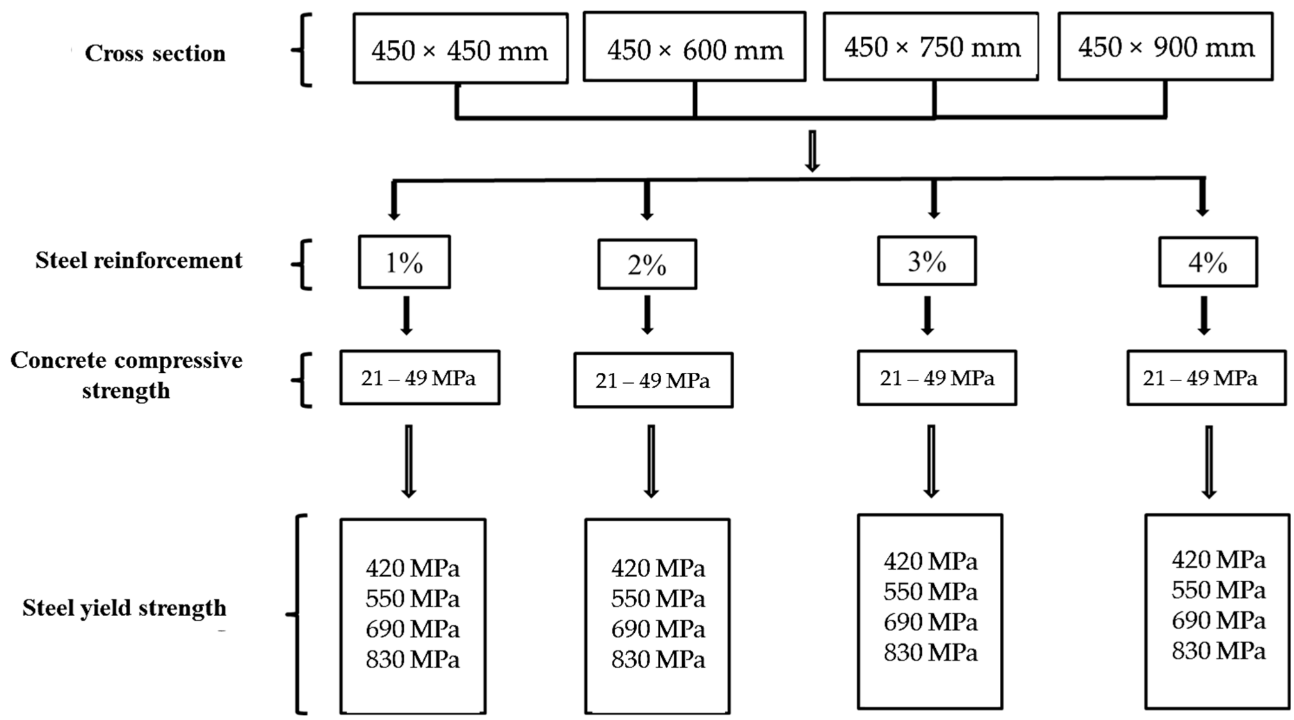

Figure 1. Flow chart for the scheme of analysis.

In order to compensate for the effects of an unintentional high yield strength on an RC column design, a reduction factor was introduced using multivariable regression analysis. It would be a conservative approach to address the variability of a yield strength up to 830 MPa. The revised design equation for a minimum tie spacing in a shear design was also proposed.

3. Results and Discussion

3.1. Comprehensive Parametric Study

Figure 2 shows the load–moment interaction diagram for a 450 × 450 mm column section at different reinforcement ratios for a yield strength ranging from 420 to 830 MPa at a 21 MPa concrete compressive strength. It can be seen that with the increase in the yield strength of a steel rebar load corresponding to balanced condition drops, a tension-controlled region is reduced. This effect is more prominent at higher reinforcement ratios, and even the balance load is found to be tensile rather than compressive, governing compressive controlled failure. The parameter of concrete compressive strength was also investigated; with the increase in concrete compressive strength, the balance load and balance moment capacity of the column were increased, but with an increase in yield strength, the balance load dropped at all values. When different cross sections were examined, the same results were observed.

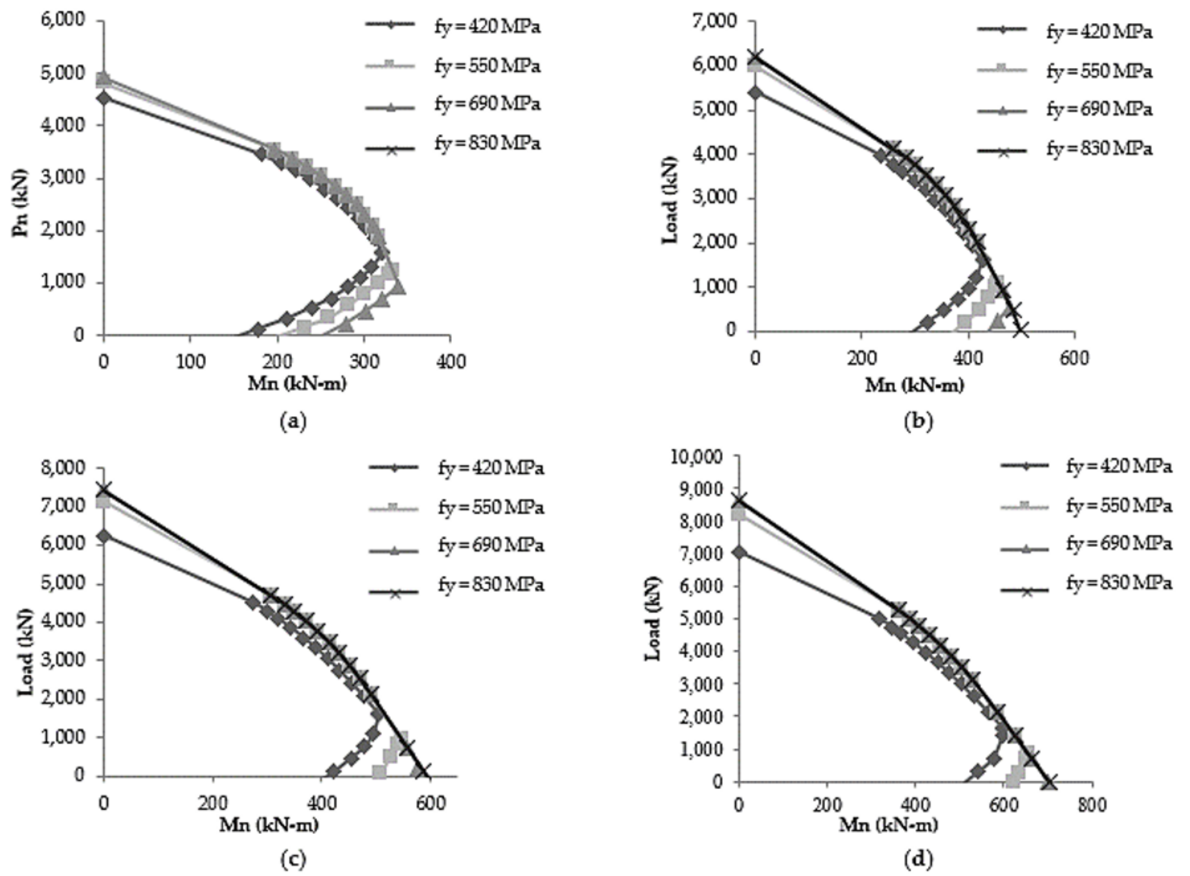

Figure 2. Load–moment interaction diagrams for 450 × 450 mm at a 21 MPa concrete compressive strength corresponding to (**a**) 1%, (**b**) 2%, (**c**) 3%, and (**d**) 4% reinforcement ratios.

Figure 3 depicts the effect of an increasing yield strength on pure axial load, balancing load moment, and pure bending moment to further elaborate the aforementioned discussion. The load and moment values are normalized by employing a 420 MPa yield strength. It demonstrates that when the yield strength increases, the balance load decreases, and this decrease is particularly pronounced at higher reinforcement ratios. The moment corresponding to the balanced condition is shown to increase as the yield strength increases, and this impact is more pronounced at higher reinforcement ratios. Furthermore, the pure axial load enhanced as the yield strength increased, with a more pronounced impact at higher reinforcement ratios.

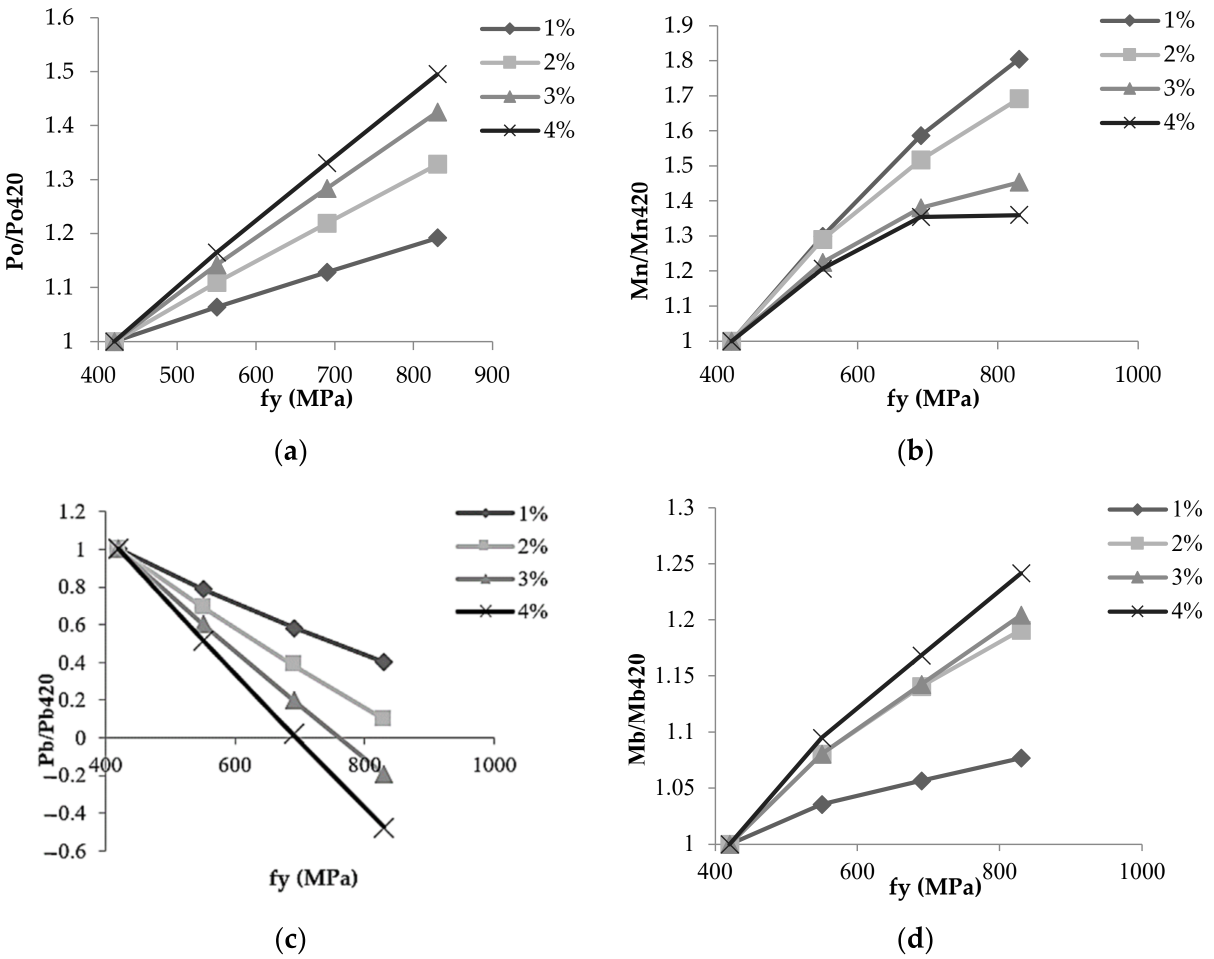

Figure 3. Effect of the yield strength of a steel rebar on the (**a**) axial load, (**b**) pure bending moment, (**c**) balance load, and (**d**) balance moment of a 450 × 450 mm column at a 21 MPa concrete compressive strength.

The effect of an increase in yield strength is also investigated for the case of biaxial bending. Figures 4 and 5 depict the 3D load–moment interaction failure surface of a 450 × 600 mm column cross section at yield strengths of 420 and 830 MPa corresponding to a 1% reinforcement ratio and a 21 MPa concrete compressive strength. It shows that the balance load drops for both axes; consequently, a tension-controlled region is reduced. It is found that the balance moment for both axes increases with an increase in yield strength. Axial load carrying capacity and pure bending moment are also found to be increased.

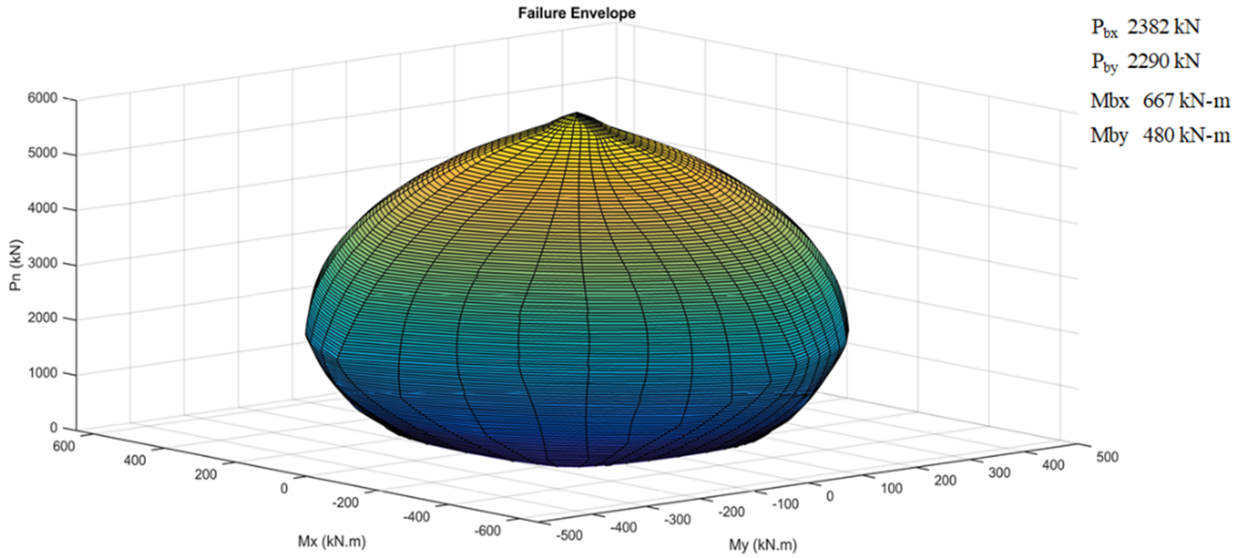

Figure 4. Three-dimensional load–moment interaction failure surface for a 450 × 600 mm column cross-section corresponding to a 1% reinforcement ratio and a 21 MPa concrete compressive strength at a yield strength of 420 MPa.

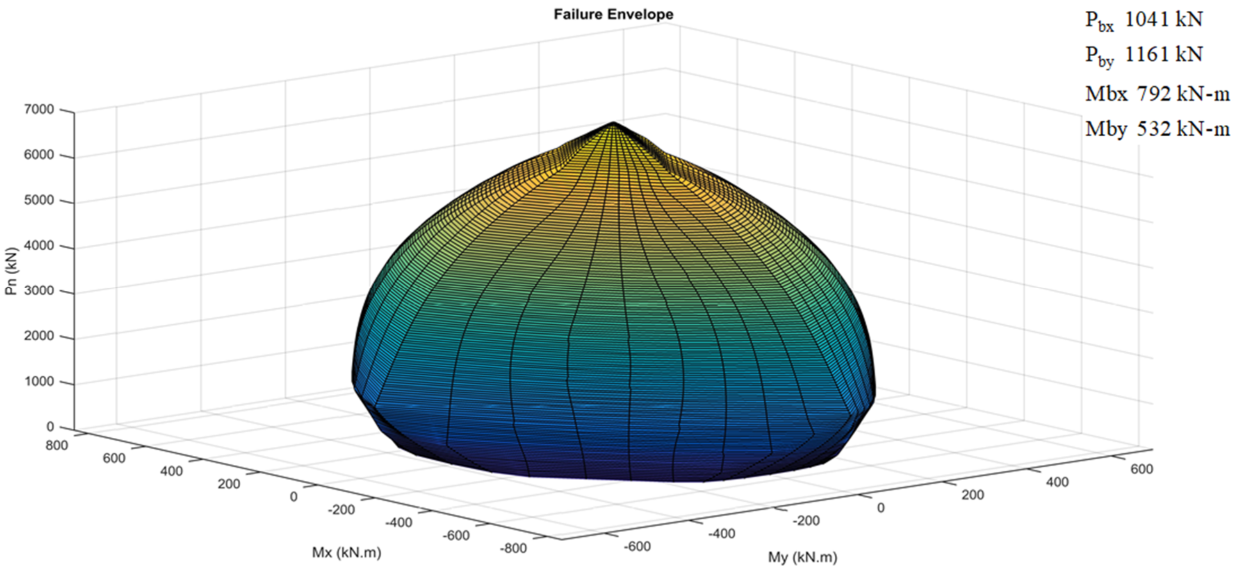

Figure 5. Three-dimensional load–moment interaction failure surface for a 450 × 600 mm column cross section corresponding to a 1% reinforcement ratio and a 21 MPa concrete compressive strength at a yield strength of 830 MPa.

3.2. Reduction Factor

It is concluded from the comprehensive parametric study that changing the area of steel, concrete compressive strength, and employing a different column cross section do not prevent the dropping of a balance point with an increase in the yield strength of a steel bar; thus, a reduction factor is introduced to compensate for the effects of an unintentional higher yield strength on the behaviour of an RC column. The reduction factor is calculated using multivariable regression. The steps of multivariable regression analysis are given below:

1. A balance load is selected at yield strength values of 420 MPa (ideal case) and 830 MPa (worst case) from the load–moment interaction diagrams at all concrete compressive strength values (20–60 MPa) for a reinforcement ratio ranging from 1% to 4%.

2. A factor Z is calculated by dividing a balance load at a yield strength of 830 MPa (worst case) by a balance load value at a yield strength of 420 MPa (ideal case).
3. Based on the comprehensive parametric study, concrete compressive strength and reinforcement ratio are two variables selected for the analysis, where reinforcement ratio is limited until the positive balance load values at a maximum yield strength of 830 MPa (worst case). Please note that yield strength is not considered an input variable since it is unknown and uncertain, and a column cross section is also not considered an input variable in order to keep the equation independent of column dimensions.
4. A multivariable regression, as shown in Figure 6, is performed on the Z factor, concrete compressive strength, and reinforcement ratio to obtain Equation (1):

$$Z = 0.00808 f'_c - 0.1463\rho + 0.3384 \quad (1)$$

where f'_c is the concrete compressive strength (MPa), while ρ is the reinforcement ratio (%).

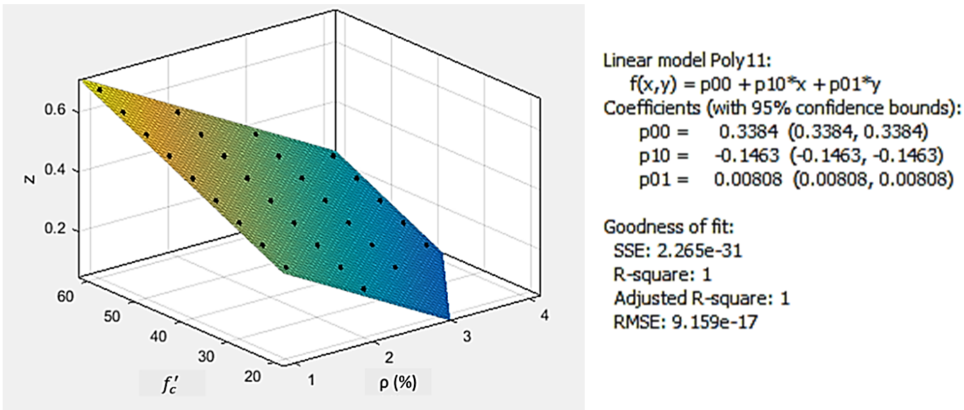

Figure 6. Surface plot of multivariable regression analysis.

Because of the variability in yield strength of a steel rebar, load values at and below the balance point of an interaction diagram employing a 420 MPa yield strength should be multiplied with the Z factor to obtain the same tension control region as that of an 830 MPa yield strength. Figure 7 depicts the factor's application to a 450 mm × 450 mm column with 1% reinforcement and a concrete compressive strength of 21 MPa.

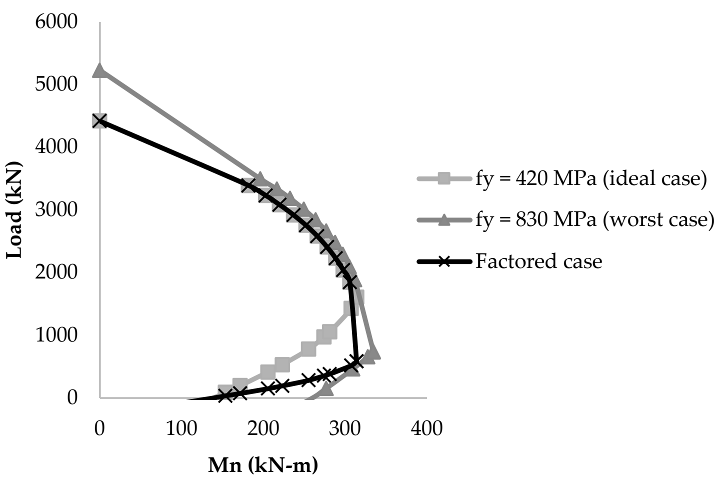

Figure 7. Load–moment interaction diagrams for a 450 × 450 mm column at a 21 MPa concrete compressive strength and a 1% reinforcement ratio corresponding to ideal, worst, and factored cases.

4. Conclusions

Based on the study, the following conclusions are drawn:

1. The comprehensive parametric study reveals that a load corresponding to a balance condition drops with an increase in rebar yield strength; consequently, a tension-controlled region is reduced. This is a drastic effect of an unintentional higher yield strength on the behaviour of an RC column, as the failure mode changes from ductile to brittle.
2. A reduction factor (Z) is introduced using multivariable regression analysis to compensate for the effect of an unintentional higher yield strength on the behaviour of an RC column. This Z factor should be multiplied with the balance load of a 420 MPa rebar yield strength (ideal case) to generate the same tension-controlled region on an interactor diagram as that of an 830 MPa rebar yield strength (worst case).

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