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Interaction Curves For Retrofitted Columns

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Abstract

Damaged columns are often strengthened or retrofitted by adhering steel plates or laminated composite plates (laminates) on the periphery of the columns. The degradation in strength before retrofitting and the enhancement in strength after retrofitting are difficult to estimate due to the odd shape of the section resulting from damage. Interaction curves for rectangular and circular cross-sections are available in published literature, but procedures for generation of interaction curves for damaged and retrofitted columns are not readily available. This paper presents a scheme for development of interaction curves for such damaged and retrofitted columns enabling more accurate evaluation of the capacity of the column, before and after retrofitting.

1. Introduction

Columns often undergo damage due to various conditions such as corrosion, accidents, overloads due to forces like earthquakes, etc. In most such conditions, it is often found that corners of the column get chipped or spalled off, thereby exposing the steel bars. If the damage is severe, the structure may need to be demolished and reconstructed. But in cases like corrosion, the damage to bars near the surface is severe, but the core or inside concrete and bars are healthy. In such cases, the obvious choice may be to repair or retrofit the columns.

Before the advent of laminated composites, such columns used to be strengthened by attaching steel plates to the outside surface of the columns. These plates may be attached by shear connectors which would be effectively transferring the forces through the concrete column to the strengthening plates and vice versa. Laminated composites have recently become the material of choice for retrofitting such columns. Laminated composites offer various advantages over steel such as better corrosion resistance, light weight, etc. Further, the composite laminates can be attached to the concrete column by adhesively bonding it, which makes the process quite simple and hassle free. The prime disadvantages that laminated composites have are the lower modulus of elasticity and the cost. The cost factor may be weighted out by the fact that if properly selected, laminated composites retrofits do not need any surface treatment for prevention of corrosion [1]. The lower elasticity modulus is a problem, but that may be mitigated by careful selection of materials and design.

Analysis of RCC column sections usually involves determination of moment capacity of the section for a given value of axial compression or vice versa. Since the section is under the effect of direct compression along with bending, the capacity of the section is a function of both the actions. Thus, a column section does not have a unique value of strength, but a failure surface is required to be computed. If the load point, characterized by axial compression and bending moment falls inside the failure surface, the column is deemed to be safe, unsafe otherwise. A vertical section of the failure surface, taken in the direction of the applied moment is termed as interaction curve. An interaction curve shows the relation between the moment carrying capacity of the section for varying values of axial compression. Such curves are of extreme importance in analysis and design of compression members. Interaction curves for rectangular and circular sections are available in published literature [2]. Park and Pauley [3] give interaction curves for regular channel sections. Non-linear behaviour of steel-concrete column sections subjected to bi-axial loading has been studied by de Sousa and Caldas [4]. They also compared various theories available for combining the influence of bi-axial bending moment on a cross-section under axial compression and developed a new capacity envelope. Razdolsky [5] developed a methodology to estimate buckling of laced columns. Chen [6] presented an iterative quasi-Newton for the rapid sectional analysis and design of short concrete-encased composite columns of arbitrary cross section subjected to biaxial bending. The stress resultants of concrete were evaluated by integrating the concrete stress-strain curve over the compression zone. El-Tawil S and Deierlein [7] proposed a method for determination of strength and ductility as a function of the percentage of steel. Narayanan and Kalyanraman[8] propose the design of column sections to be performed by giving considerations to the plastic capacity of the loaded column section. They also generate an interaction curve for a composite column section in order to determine the capacity of the section using the simplified design method suggested in the UK National Application Document for EC4. SP16 offers interaction curves for RCC column sections under axial compression and uniaxial bending as per IS:456 (2000) [9]. However, the design curves as per design approach of IS:456 (2000) are not yet available for damaged and retrofitted column sections. This poses difficulties in estimating the capacity of such column sections considerably and subsequently designers are usually unable to be confident about the remaining capacity of the damaged section or the enhanced capacity of the retrofitted section. The axial compression interacts with the flexural stress in a non-linear fashion, making it difficult to estimate the exact capacity of a given section. Thakkar [10] developed a framework for generation of interaction curves for encased columns, but of regular cross-section shapes. A scheme for generation of interaction curves and the underlying assumptions have been discussed here. Further, interaction curves have been generated along with the strength envelope. Having developed the framework, a parametric study for various laminate thicknesses has been carried out and interaction curves for various ply thickness such as 4mm, 6mm, 8mm and 10mm are shown.

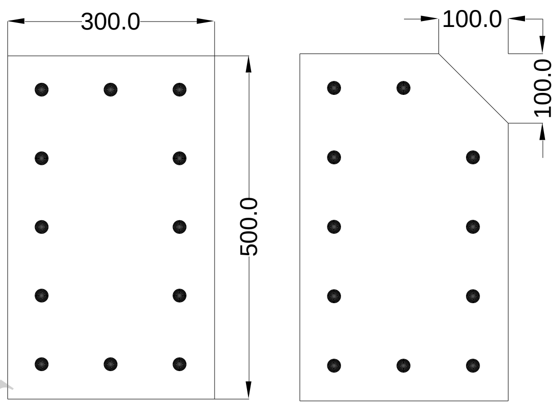
2. Laminated Composites

Composites are materials made up by mixing two or more materials to combine the good qualities of each constituent material. High strength fiber made of glass, carbon, aramid, boron, etc. may be embedded in a matrix to form a ply or a lamina. When number of such plies or laminas stacked, a laminate is formed. Laminated composites may be designed to obtain the required properties by controlling the ply characteristics and the stacking sequence of plies. Since the fibers and the matrix may be glass, or a non-metallic material, laminated composites have a very good corrosion resistance and fire resistance. While being light in weight, laminated composites are also known to be having very good fracture toughness and fatigue resistance. Due to these favourable properties, laminated composites have rapidly become a material of choice for retrofit.

The inclusions in laminates may be particulate, short fiber, long unidirectional fiber or woven fabric. Each type has its properties and relevant applications. For retrofit of civil engineering structures, usually unidirectional fiber reinforced polymers or woven fabric embedded in a polymer matrix are preferred. The main reason behind this choice is the ease of application of the retrofit and the economy of the material. Characteristics of the laminate may be designed based on the orientation of the fibers in the ply and the position in the laminate. Of all the types of laminated composites, E-Glass/epoxy type laminates are usually preferred owing to their relative economic availability.

3. Retrofit of Columns

In most general cases, corrosion affects the bars towards the exposed surface. As a typical case, the corner bar in a rectangular column has been assumed to have been chipped off. A schematic of the original rectangular column along with the idealized damaged column is shown in □□□ I.



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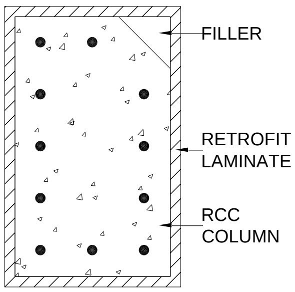
To retrofit the column, it may be encased from outside by applying laminated composite plates on the periphery. This would certainly enhance the strength of the column, but it becomes very difficult to estimate the behaviour of the column under axial compression and bending moments. For facilitating easy estimation of the capacity of the compression member under axial compression and bending, appropriate methods are required to generate interaction curves for the retrofitted section.

4. Generation of Interaction Curves

Generation of interaction curves for retrofitted columns require rigorous computations if the retrofitting laminates contain angle plies in the stacking sequence. However, normally woven fabric or unidirectional laminates are used as retrofitting material with the material axis aligned with the longitudinal axis of the columns. This greatly simplifies the problem of computation of stress block over the laminate section. The difficulty however arises in calculation of the stress block of the concrete section, which is not rectangular in shape. In such cases, the discretization of the section becomes important. The RCC portion of the section is discretized in such a way that the calculation of the stress block over each segment is easily possible. Care has to be taken when the neutral axis intersects the inclined portion of the section. A schematic of the retrofitted column is shown in □□□ ı. A typical discretization of the section when the neutral axis intersects the inclined (damaged) portion of the RCC section is shown in □□□ ŏ. Typically, the damaged portion of the section is filled by some light filler material. This portion is ignored in the current analysis to be carrying any form of load and is subsequently ignored during the stress balance calculations.



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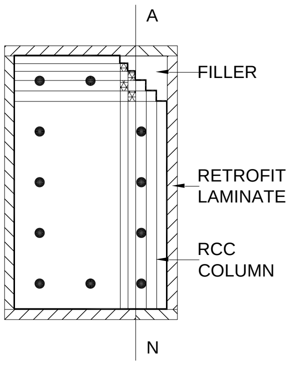

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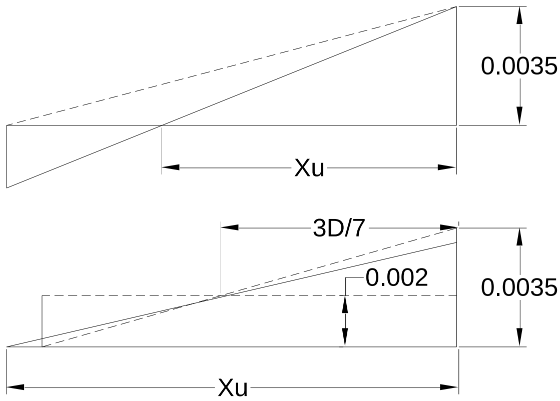
The approach adopted here follows the framework laid down by BIS in SP:16 [2]. The strain variation adopted for the section under axial and bending actions when the neutral axis lies inside and outside the section is considered as shown in □□□ ŏ.



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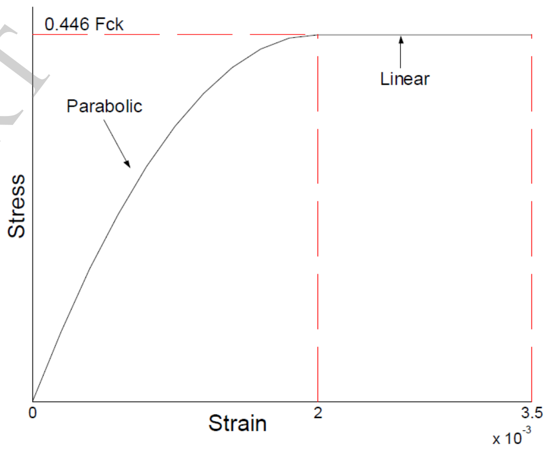
Linear strain distribution is adopted over the section confirming to the classical theory of bending as suggested by IS:456 (2000). Based on the strains at each point, the value of stress can be computed. The stress corresponding to strain for concrete is considered as per IS:456 (2000) and is reproduced in □□□ .



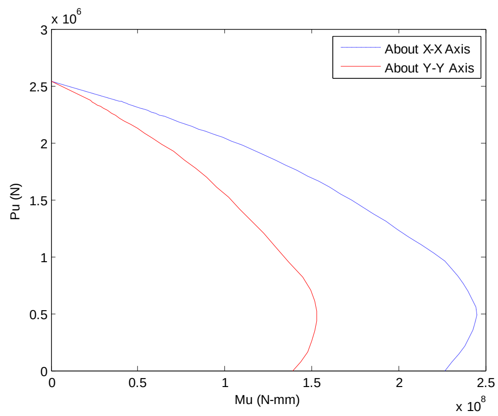
Stress in concrete varies parabolically with strain till a strain value of 0.002. Beyond that, the stress is constant and equal to 0.446 *fck*. The fulcrum point of strain value 0.002 must be maintained for all positions of the neutral axis. When the neutral axis is inside the section, the strain values in the most compressed edge may exceed 0.0035. This imposes a limit on the position of neutral axis. On the other extreme, the neutral axis at infinity characterizes the condition of purely axial compression, which is analysed without determining the position of neutral axis. SP16 suggests that it is sufficient to consider neutral axis 1.5D beyond the edge of the section. This helps in setting a better initial guess of neutral axis position and speeds up the root finding algorithm. For each location of neutral axis 'Xu', the stress diagram can be obtained. Similarly, value of stresses at steel bar locations can also be computed, by considering the stress-strain diagram for steel reinforcements. For every position of neutral axis, the cross-section must be re-meshed. Since the discretization of the section approximates the inclined sides as stepped, the meshing algorithm becomes extremely simple but mesh sensitive. Large number of steps on the inclined portions of the section would improve the results. Calculation of stress block parameters for a rectangular region becomes trivial. Hence, the equations for calculating stress block parameters have not been discussed here. The stress variation with respect to strain for the steel bars is considered to be linear. It is also assumed that the value of stress is averaged over the area of each bar, which corresponds to the value of strain at the centroid of the bar. The compressive stress in steel for a given strain is considered as per the recommendations of IS:456. A linear stress variation has been assumed for the retrofitting laminate. Also, the behaviour in tension and compression has been considered to be similar.

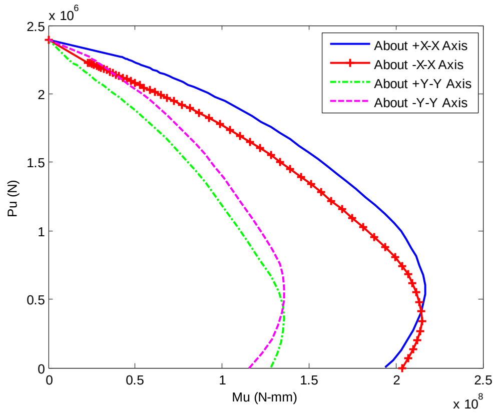
For each position of neutral axis, the section needs to be divided into rectangular segments. For each segment considered, the corresponding strain in the element at either edge is computed and subsequently the volume of stress block is obtained. The only care that needs to be taken while dividing the section in segments is that the segments must have edges parallel to the neutral axis, otherwise the calculation of stresses over the segment become cumbersome. The contribution of each element of the section to the volume of stress block is added to the volume of stress block obtained for the section and the total axial load that can be carried is computed. The contribution of the element to the moment capacity is similarly computed. To compute each point on the interaction curve, the axial load 'Pu' is incremented from 0 to 'Pcr', where 'Pcr' is the total axial compressive load capacity of the column in absence of bending moments. For each value of intermediate 'Pu', the value of 'Xu' must be determined, which in turn dictates the strain variation over the section and thus the stress variation. The stress variation is used to compute the value of axial load and bending capacity of the section. Thus, the value of 'Xu' must be calculated by non-linear iterative procedures. Nonlinear solution has been performed here by Brent algorithm [11]. Another efficient algorithm would be to increment the neutral axis position from the position computed for the case of pure bending moment up to 1.5D. While incrementing the neutral axis position, the values computed for Pu and Mu must be accumulated and use subsequently in plotting the interaction curves. This approach is significantly faster compared to the previously mentioned approach whereby the axial compression is incremented, and the position of neutral axis is determined by iteration.

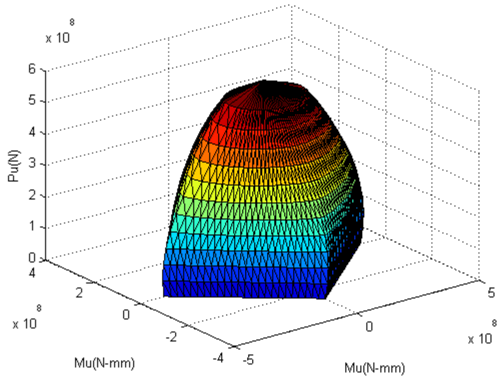
5. Analysis of Damaged Section

Employing the scheme discussed above, interaction curves have been generated for the undamaged and damaged sections. While the interaction curves for undamaged section give a very good idea about the original strength of the column before degradation, it also serves the purpose of validating the algorithm as the curves can be readily compared with those published in SP:16.

Interaction curves depend upon the direction about which the bending action is considered. This is primarily due to the fact that the moment capacity depends on the moment of inertia about any given axis. Hence, the section has different moment resisting capacity in both x and y directions. Further, for unsymmetrical sections the moment resistance also varies based on the sign of the applied moment. Hence, ideally, four interaction curves would be obtained for any unsymmetrical section. For a symmetrical section the interaction curves would overlap. Interaction curves for undamaged cross section are shown in □□□ . Interaction curves along all four axes (positive x, negative x, positive y and negative y) have been generated and reported for the damaged section in □□□ . It is clear from the plot that there are four interaction curves for the section. Of course, the curve to be considered depends upon the design problem at hand.







The interaction curves presented in SP:16 are normalized with the dimensions of the cross-section considered. While such normalization makes the charts generalized for any cross-section having the shape considered while generation, such normalization is not possible here because of the irregularity in shape of the cross section. Another very important aspect of column capacity is the strength envelope. The strength envelope can be said to be the envelope obtained for a given value of axial compression Pu with varying directions of neutral axis. Thus, strength envelope can also be said to be a horizontal cross section of a 3-D capacity or failure surface, whereas interaction curves can be visualized as vertical cross section of the 3-D capacity surface. IS:456 (2000) considers a power law for combination of the moments from both sides. This method may not be required here as the strength envelopes are generated by rotating the neutral axis before computing the moment capacity. E-glass epoxy laminate having E_1 = 38.6GPa, E_2 = 8.27GPa and ν = 0.26 [1] is considered for retrofitting the damaged RCC column, whereas concrete of grade M20 and steel grade Fe415 have been considered for the RCC column. The full 3D capacity surface with neutral axes rotated 360^o for the section retrofitted with 10mm thick laminate is shown □□□ . Such a surface proves to be important for designing the column sections as precise moment capacity of the section is available for any given direction. Thus, a biaxial moment may be converted to a resultant uniaxial moment with a rotated neutral axis.

6. Parametric Study

Retrofitting of a column is usually done to enhance its performance or increase the strength. In such cases, it becomes vital to obtain a comparison of the enhancement in strength with respect to the thickness of the laminate adhered to the column surface. Interaction curves have been generated for varying thickness of the retrofitting laminate and have been reproduced in Figure 9. Laminate thickness has been varied from 4mm to 10mm in steps of 2mm. Curves designated as a, b, c and d in the figure show the interaction between axial compression and moment about the Y-Y axis of the section having retrofitting laminate thickness of 4mm, 6mm, 8mm and 10mm respectively. Whereas, the curves designated as 1, 2, 3 and 4 respectively show the interaction about X-X axis for section with laminate thickness of 4mm, 6mm, 8mm and 10mm respectively. Having the interaction curves, it would be possible to decide the required thickness of laminates based on the design loads and moments.

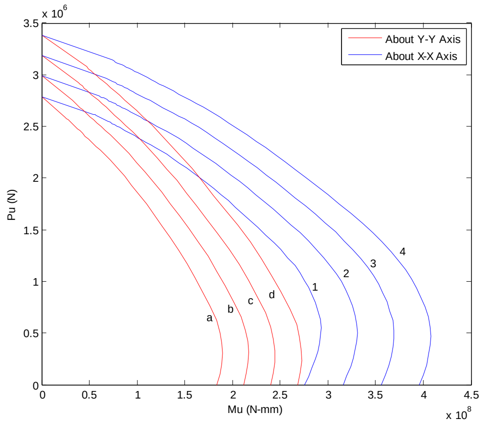


Figure 9: Interaction Curves: Retrofitted Section

6. Conclusion

A methodology developed for generation of interaction curves and strength envelope of damaged and retrofitted column sections has been presented here. Interaction curves and 3-D capacity surface have been reproduced, which indicate the strength of the section in each direction. The methodology appears to be promising and tries to give a more robust technique for analysis of RCC retrofitted column sections.

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