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Grade 500 Reinforcement: design issues with L, N and E grade reinforcing steel and the overstrength of pacific steel micro alloy reinforcement

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ABSTRACT: Using the principles of capacity design it is necessary to be able to predict the maximum strength of the yielding elements in a structure. The ratio of the maximum moment capacity divided by the nominal moment capacity is commonly called the overstrength factor for a reinforced concrete member. With the introduction of Grade 500 reinforcement into the marketplace it is necessary to determine the change in the overstrength factor compared to that for Grade 430 reinforcement. This paper presents the results obtained from an analytical study aimed at determining the overstrength factor for concrete members with Grade 500 reinforcement as longitudinal steel.

1.0 INTRODUCTION

With the introduction of Grade 500 reinforcement into the marketplace in New Zealand a number of unresolved design issues still remain. These include the bond between the reinforcement and the concrete, the development length between reinforcing bars, and the overstrength factor of members constructed with Grade 500.

The overstrength factor is defined as the ratio of the maximum strength of a concrete member, M_{max}, to the nominal strength of the concrete member, M_n. The nominal capacity is usually calculated using the lower 5th percentile yield strength of the reinforcement [1]. The overstrength ratio is used to ensure that the strength of all other elements in a reinforced concrete structure are stronger than the maximum possible strength of the element that has been chosen to deform in an inelastic manner. The ability to accurately determine the maximum overstrength capacity of an inelastic member is the fundamental principal in “capacity design”. A full description of the principles of capacity design are provided elsewhere [2, 3].

The most common elements chosen to undergo inelastic deformations are the end regions of the beams and the base of the columns. This form of inelastic behaviour is defined as a “weak-beam strong-column” mechanism.

This paper presents the preliminary results in a study aimed at determining the overstrength factor for reinforced concrete beam and column members constructed using Pacific Steel Micro-Alloy Grade 500 longitudinal reinforcement.

2.0 VARIABLES INVESTIGATED

The overstrength ratio of a reinforced concrete beam or column is dependent on a large number of inter-related variables. The variables that were investigated in this study are discussed below.

2.1 Section Shape:

The investigation was limited to column members of rectangular and square cross section and rectangular beam members. The width and depth of the column members was varied between 400 mm and 1000 mm, in 100 mm increments. Similar dimensions and increments were used for the beam members. In no situations was the width of the member specified greater than the depth.

T-beams were not investigated, as research being undertaken at the University of Canterbury has indicated the current design procedures for determining the effective tension and compression flanges of T-beams may need updating. It is expected that a further series of analyses will be completed on T-beams once the design rules have been revised.

2.2 Steel Content:

The longitudinal steel content was varied between the maximum, p_{max}, and minimum, p_{min}, allowed in the New Zealand Concrete Structures Standard, NZS3101: 1995 [5]. All of the longitudinal reinforcement was uniformly distributed, with even spacings, around the cross section of the column members. The ratio of compression steel to tension steel (p'/p) was varied between 0.5 and 1.0 in the beam members.

2.3 Transverse Steel:

The diameter and yield strength of the transverse reinforcement used in the beam and column analyses are shown in Table 1. The yield strength was determined as the upper 95th percentile yield strength for both Grade 300 and Grade 500 reinforcement recorded by Pacific Steel Limited over the range of different bar diameters.

Table 1 Transverse Steel Yield Strengths

Bar Type	**95%ile f_y (MPa)**
XR12	604
XR16	651
R12	345
R16	356

The spacing of the transverse reinforcement in the column members was based on the column confinement and the anti-buckling requirements of NZS3101: 1995. The anti-buckling requirements were used to determine the spacing of the transverse steel in the beam members.

2.4 Concrete Strength:

Four concrete compressive strengths were investigated. Based on information provided by Allied Concrete [4], the mean 28 day concrete compressive strength values were used in the analysis. The specified and actual 28 day concrete compressive strengths used in the analyses are shown in Table 2 below.

Table 2 Specified and Actual Concrete Strengths

Specified f'_c (MPa)	**Actual f'_c (MPa)**
25	33
30	39
35	42.5
40	50.5

2.5 Longitudinal Steel:

The behaviour of reinforcing steel can be predicted by knowing six key variables; yield stress and strain (f_y, ε_y), strain at the onset of strain hardening (ε_{sh}), ultimate stress and the corresponding strain (f_u, ε_u), and the modulus of strain hardening (E_{sh}). A full description of these variables is provided elsewhere [6].

Pacific Steel has undertaken an extensive testing programme on Grade 500 reinforcement, recording approximately 1000 load-deformation responses. The six key variables were determined for each of the tested samples, forming a database of material properties.

The longitudinal reinforcement used in this study was limited to XD20, XD25 and XD32 reinforcing bars ("X" is a temporary designation for Grade 500 reinforcement). The material properties for each type of reinforcing bars were determined directly from the database obtained from Pacific Steel. Previous studies to determine the overstrength factor of reinforcing concrete members have randomly generated the longitudinal reinforcing steel properties using statistical methods. This method does not fully compensate for the interaction between the six variables.

2.6 Axial Load:

The level of axial load resisted by a column can be expressed as an axial load ratio, $N/A_g f'_c$, where N is the applied axial load, A_g is the gross area of the section, and f'_c is the concrete compressive strength. Columns in lateral load resisting frames, subjected to earthquake forces, are not usually subjected to high level of imposed axial load. As a result, the column members analysed in this study were subjected to low axial load ratios of 0.1 and 0.3.

2.7 Curvature Ductility:

Curvature ductility is a measure of a structural member ability to undergo inelastic rotations. The New Zealand Concrete Structures Standard, NZS3101: 1995, [5] implies that limited ductile members should achieve a curvature ductility of 10, and fully ductile members achieve 20.

The overstrength factors of the column and beam elements investigated in this study were determined at curvature ductility levels of 10, 15, 20 and 30.

3.0 ANALYSIS METHOD

A series of monotonic moment-curvature analyses were completed on the beam and column members to provided a theoretical moment verses curvature response. From the recorded responses the overstrength factors were calculated for curvature ductilities of 10, 15, 20 and 30.

The behaviour of the concrete was modelled using the Mander stress-strain response for confined and unconfined concrete. A full description of the Mander model is provided elsewhere [7].

The longitudinal reinforcement in the beams was modelled using the monotonic steel stress response derived by Mander et al [7], using the six key variables for each reinforcing bar obtained by Pacific Steel. It has been shown in the past that a monotonic response provides an accurate representation of the behaviour of longitudinal reinforcement in beam members where the steel is subjected to large tensile strains and small compressive strains [8].

The longitudinal reinforcement in the column members was modelled using the same stress-strain response as the beam members. However an additional pseudo-cyclic function was added to allow for the cyclic nature of large tensile and compressive strains imposed on the reinforcing. A full description of the pseudo-cyclic function is provided elsewhere [8].

Combinations of all of the variables for each cross sectional shape and member type described in the previous section resulted in approximately 350,000 analyse being completed.

4.0 RESULTS

The results obtained from the moment-curvature analyses were investigated to determine the influence of each of the variables on the overstrength factor for the beams and columns. The full series of results are presented elsewhere [19]. A brief summary of the results for the beams and columns is provided below:

4.1 Beam:

- The overstrength factor obtained from the entire series of analyses provided a good fit to a normal distribution.
- Based on previous research and on common statistical practices the overstrength value presented above was determined as the upper 95th percentile overstrength factor from the normal distribution, with a 95 percent confidence interval [1].
- The cross section dimensions, longitudinal steel contents, transverse steel type, concrete strength, and level of curvature ductility did not significantly affect the measure overstrength factor.
- The most significant variable affecting the overstrength factor for the beam elements was the material properties of the longitudinal reinforcement.
- The overstrength factor for the beam elements with Grade 500 reinforcement was found to be 1.40.
- The results obtained in this study are only applicable to Grade 500 reinforcing bars produced by Pacific Steel.

4.2 Columns:

- As with the beam analyses the overstrength factor presented above was obtained as the upper 95th percentile from the normal distribution with a 95 percent confidence interval.
- The cross sectional dimension, concrete strength, longitudinal steel content, and the transverse steel type and diameter did not significantly affect the overstrength factor for the column elements
- The most significant variables affecting the overstrength factor for the column members was the applied axial load ratio, the curvature ductility and the material properties of the longitudinal reinforcement.
- A detailed statistical review was undertaken on the column results to produce a single conservative overstrength factor that can be used for all column elements with axial load ratios under 0.6.
- It is the author’s recommendation that an overstrength factor of 1.35 could be adopted for all column elements.

The results presented above for the beams and columns were based on a results obtained from the testing of Grade 500 reinforcing bars. Pacific Steel is currently making alterations to the chemistry of the Grade 500 reinforcement to reduce the variation in the yield strength and reduce the ratio of yield to ultimate strength. This alteration in chemistry should result in a lower overstrength factor than what has been presented above.

This study is an ongoing project and the final presented overstrength factor will be based on the final chemistry determined by Pacific Steel. However, the numbers presented above are correct of the current chemistry of Grade 500, produced by Pacific Steel, on the market.

5.0 L, N AND E GRADE REINFORCEMENT

The advent of the Joint Australian/New Zealand Standard AS/NZS 4671:2001, “Steel Reinforcing Materials” [9] has resulted in the introduction of three classes of Grade 500 reinforcement into the New Zealand marketplace. A number of design issues have been raised for the classes of Grade 500: L, N and E, with respect to elongation capacities of each, as well as bond performance, stiffness of members, flexural overstrength and site issues.

The mechanical properties of the new steels, specified by characteristic values, are summarised in Table 3. $R_{ek,L}$ and $R_{ek,U}$ are the lower and upper characteristic yield stress of the material respectively, R_m is the ultimate tensile strength, and A_{gt} is the strain in the steel corresponding to the maximum stress in the bar, also defined as the uniform elongation.

Table 3 Mechanical Properties of Reinforcing Steel

Property		500L	500N	500E	430
Yield Stress	$R_{ek,L}$	500	500	500	410
	$R_{ek,U}$	750	650	600	520
Ratio	R_m/R_e	1.03	1.08	1.15	1.15
		-	-	1.40	1.50
Elongation	A_{gt} (%)	1.5	5.0	10.0	10.0

The change from Grade 430 reinforcement to Grade 500 will have a number of implications in the behaviour of concrete structures. The uniform elongation, (A_{gt}) of the new Grade 500N steel has a minimum requirement that is half that of Grade 500E. In addition, Grades 500L and 500N do not have an upper limit to the ratio of the ultimate tensile stress to the yield strength (R_m/R_e).

5.1 Bond Stresses:

The development and lapping requirements presented in NZS3101: 1995 [5] were developed for reinforcing bars which develop tensile stresses under 556 MPa [10]. In certain locations, such as curtailment of bars near plastic hinge locations in the beams, it is possible for the stresses in Grade 500 reinforcing steel will significantly exceed this value. Research at the Universities of Canterbury and Auckland show that there is the potential for loss of bond on Grade 500 beam bars, passing through beam-column joints [11,12].

Pacific Steel has commissioned the University of Auckland to undertake a series of beam-column tests to help establish bond stress design rules for Grade 500 bars.

5.2 Ductility:

The majority of reinforced concrete structures in New Zealand are designed to be ductile under overload conditions by forming plastic hinges in the beam elements. Each plastic hinge zone must be capable of undergoing large amounts of inelastic deformation with little or no reduction in load carrying ability. If the longitudinal reinforcement used in the concrete member has a sufficiently large value of uniform elongation, A_{gt}, such as Pacific Steel Grade 300, 430 and 500E, then the ultimate displacement of the member may only be limited by the maximum allowable inter-storey drift of the structure.

Grade 500L and 500N reinforcements have lower allowable uniform elongation, A_{gt}. Based on the results presented in Table 3, and assuming the reinforcement has a uniform elongation capacity equal to the minimum values, then the ultimate displacement capacity of a beam constructed with Grade 500N steel would be approximately 50% smaller than an identical beam constructed with Grade 500E reinforcement.

Structures designed using Grade 500N reinforcement should use a reduced level of displacement ductility than Grade 500E. This would result in the structure being designed for a larger base shear and require bigger members and foundations. Various researchers in New Zealand and Australia have reported similar findings [13, 14, 15].

In the topping concrete on precast concrete floors units is common to place continuity reinforcement to provide deflection control and to reduce the mid-span moment in the precast prestressed concrete floor systems. In these the continuity steel needs to yield significantly at the Service Limit State. It is typically observed in floor topping that one or two large cracks develop at the interface of floor and supporting beam/wall. The local plastic deformation in the continuity bar at the location of a crack could be as large as 4-5% strain. This demand corresponds with the minimum specified uniform elongation capacity (5% or 20 e_y) required of Grade 500N and is about 3 times larger than the minimum specified uniform elongation capacity of Grade 500L (1.5% or 6 e_y).

Due to the reduced level of ductility in structure designed with Grade 500L and 500N steel it could be recommended that elements which require any form of ductility, either through seismic action, gravity moment redistribution, or imposed displacements be designed with Grade 300E or 500E as longitudinal reinforcement.

5.3 Stiffness:

In structural design it is necessary to be able to model the approximate stiffness of the elements in a building. A beam element designed with Grade 500 reinforcement will require less reinforcing steel to resist an applied moment than an identically sized beam with Grade 430. The reduced steel content of the Grade 500 beam will result in a lower stiffness (using the transformed section method).

The reduction in stiffness of members produced with Grade 500 reinforcement will need to be addressed by the Technical Committee of NZS3101 [5] to ensure the realistic estimates of member stiffness are obtained.

5.4 Flexural overstrength:

The initial section of this paper discussed the flexural overstrength factor for Grade 500 reinforcement produced by Pacific Steel. This reinforcement is designated Grade 500E.

The new steel reinforcing material standard, AS/NZS 4671: 2001 [9] does not place upper or lower limits on the ratio of the ultimate tensile stress, R_m, to the yield stress, R_e for Grade 500N and 500L reinforcement.

If the reinforcement has a large R_m/R_e ratio then there is no certainty on the amount of strain-hardening and flexural "overstrength" that may be generated. Consequently, the overstrength factor $?_o$ may be significantly higher than suggested by the authors.

However, if the ratio of R_m/R_e is too low the yielding region of a reinforcing bar will **not** propagate along the length of the bar, but rather concentrates in one location. The level of strain in the reinforcement at the location of the yielding will increase quickly and may result in the early fracture of the reinforcing bar. Grade 500N and Grade 500L reinforcement have low uniform elongation capacities making them less capable of resisting large levels of imposed strain before fracture.

In the situation of starter bars/continuity reinforcement, it is recommended that Grade 500E be used with stricter controls on the ratio of R_m/R_e to ensure yield penetration and a larger uniform strain capacity to resist the imposed displacements without fracturing. Class L mesh was seen to fail, acting as continuity steel, quite extensively in the Northridge earthquake, 1994.

5.5 Site Issues/Classification:

A number of contractors are now inquiring about using Grade 500N reinforcement for "non-ductile members". This raises the issue of steel identification on a construction site and the consequences of mis-identification.

If a Grade 300 reinforcing bar was mis-identified and placed into a yielding element designed for Grade 430 reinforcement, then the member would have a lower strength than calculated. This would not result in the premature catastrophic failure of the element as both the Grade 300, Grade 430, and Grade 500E reinforcement have large uniform elongation capacities.

With the introduction of three classes of Grade 500 steel onto the market place there is a possibility that both Grade 500N and 500E will be used on the same construction site. If a Grade 500N bar was misplaced into a primary yielding element instead of Grade 500E then the apparent design strength of the element would not be affected, but the displacement ductility of the member would be reduced. The reduced level of ductility could result in the member failing prematurely thereby placing additional loads on the surrounding elements.

6.0 CONCLUSIONS

1. The overstrength factor for beam elements using Grade 500 reinforcement is 1.40.
2. The overstrength factor for column elements using Grade 500 reinforcement is 1.30.
3. The most significant variable affecting the overstrength factor for both reinforced concrete columns and beams is the material properties of the longitudinal reinforcement.
4. Pacific Steel Limited are currently altering the chemistry of the Grade 500 reinforcement to reduce the variation in yield strength and the ratio of yield to ultimate strength. This will help to reduce the overstrength values presented above.
5. The results presented in this paper are preliminary only and will change as the database of tested Grade 500 reinforcing bars increases.
6. It is unclear whether the existing bond requirements of NZS3101: 1995 are directly applicable for use with Grade 500 reinforcement.
7. The stiffness of concrete elements designed with Grade 500 reinforcement are different to those designed with Grade 430. This needs to be addressed by NZS3101 to ensure the realistic estimates of member stiffness are obtained when using the guidelines.
8. For certain regions in slabs, plastic elongation capacity for reinforcement is desirable. It is recommended that in these situations, reinforcement should be constructed from Class E reinforcement with the strict controls on the ratio of R_m/R_e to ensure that there is reasonable yield penetration and a larger uniform strain capacity to resist the imposed displacements without fracturing.
9. Due to the reduced level of ductility in structure designed with Grade 500L and 500N steel, it could be recommended that elements that require any form of ductility, either through seismic action, moment redistribution, or imposed displacements be designed with Grade 300E or 500E as longitudinal reinforcement.

7.0 ACKNOWLEDGMENTS

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