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# ADVANCED DESIGN™ OF COLUMNS

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CCTR

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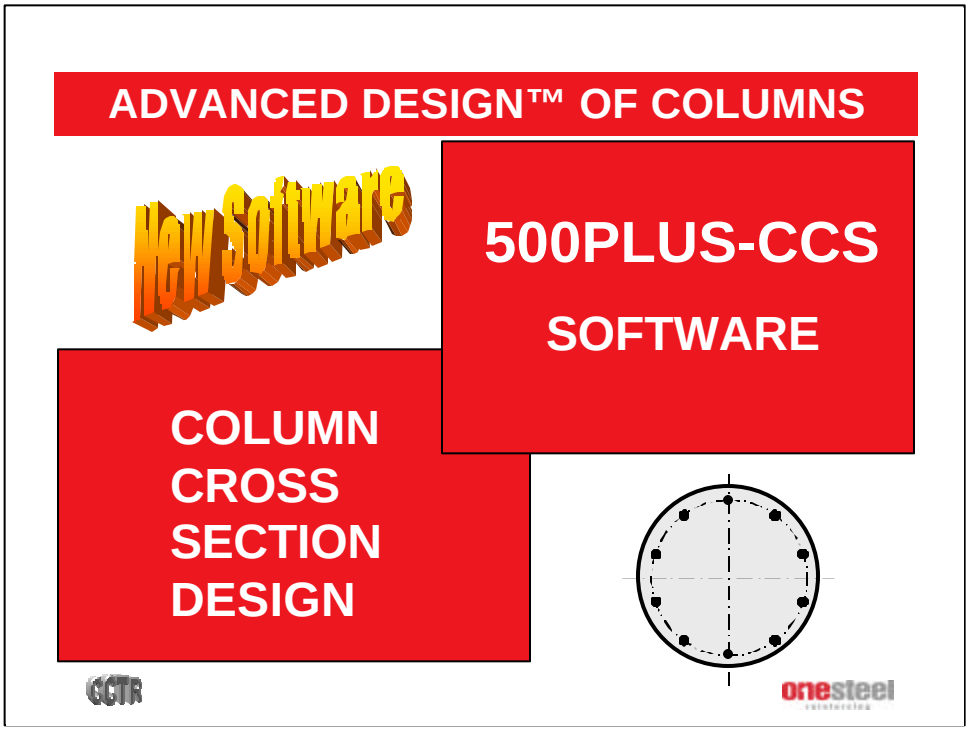
The Centre for Construction Technology and Research at the University of Western Sydney is progressively developing new design rules for OneSteel Reinforcing's *Guide to Reinforced Concrete Design*.

Top-tier design rules that meet the requirements for design by refined calculation defined in AS 3600-2001 are being released under the trademark of Advanced Design™. This presentation concerns rules being developed for advanced design of reinforced-concrete column cross-sections for strength. The design rules are proprietary and should only be used when OneSteel Reinforcing's products are specified.

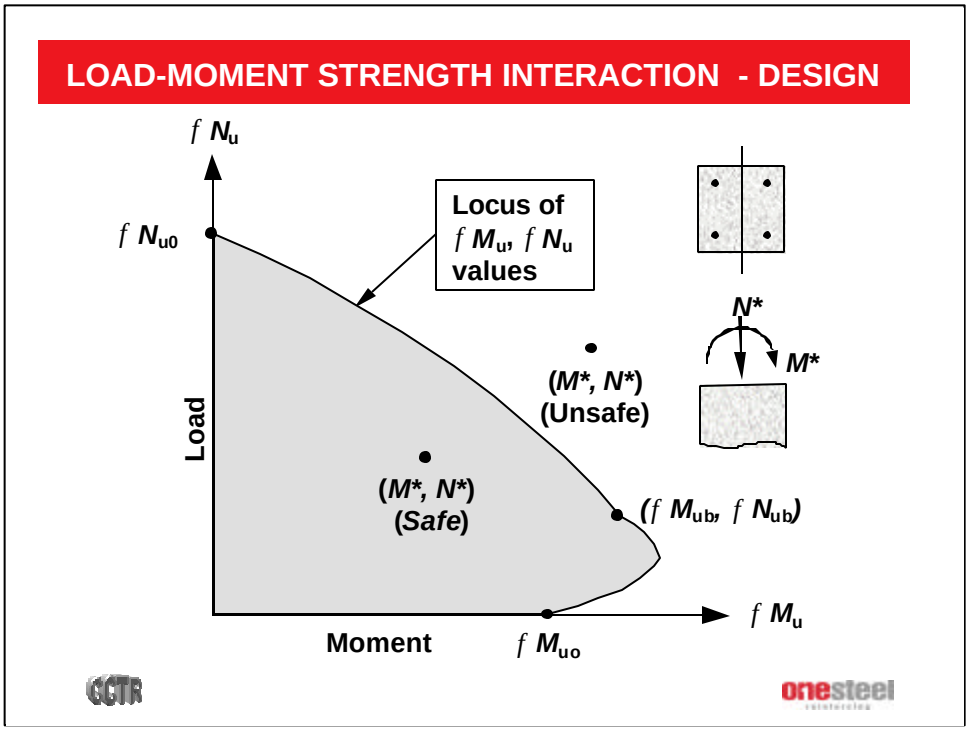



The advanced design rules have been incorporated in a new software package called 500PLUS-CCS, “CCS” standing for “Column Cross-Section” which will be demonstrated during the presentation.

The new design rules and software will provide the user with a better determination of cross-section strength and allowing the safe and economical use of higher strength materials.

The presentation looks at the design principles used in the determination of the cross-sectional strength of a conventionally reinforced column.

Also presented are the principles used in advanced analysis which was used in the development of the software package 500PLUS-CCS.




In the design of a reinforced concrete column the designer is primarily concerned with obtaining a column for which the design action effects (defined by combination of M*, N*) fall within the load-moment strength interaction diagram. Typical load-moment strength interaction diagrams as shown may be generated using either simplified methods or using advanced analysis. The 500PLUS-CCS software enables the designer to use advanced analysis methods to derive an accurate interaction diagram for design use.

The load moment strength interaction diagram is dependent on a number of factors including the geometry of the cross-section, and the material properties of both the concrete and reinforcement. One of the major advantages of the advanced analysis is the ability to accurately predict the stress in a cross section for a give strain distribution, thus providing an accurate means for determining realistic column capacities.

## CONCRETE AND STEEL MATERIALS

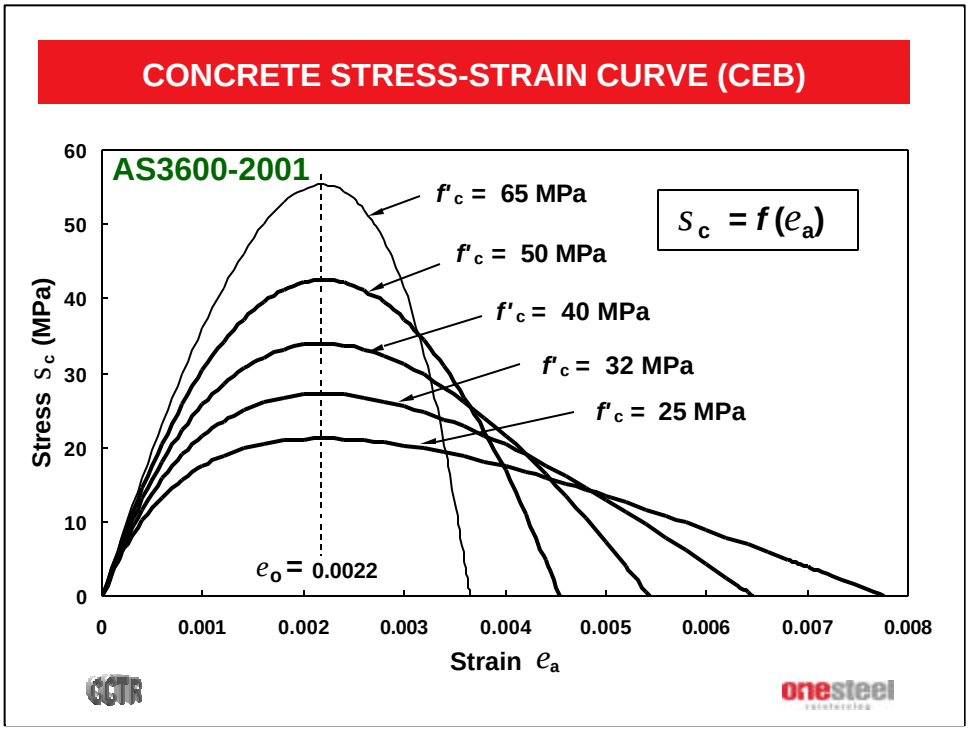
### Concrete

- Four original Grades; new Grade; high strength
- $f'_c$ = 25, 32, 40, 50 MPa; 65 MPa; up to 90 MPa
- Maximum Strength = 0.85 $f'_c$

### Steel

- 500N grade - 500PLUS â ($f_{sy}$ = 500MPa)

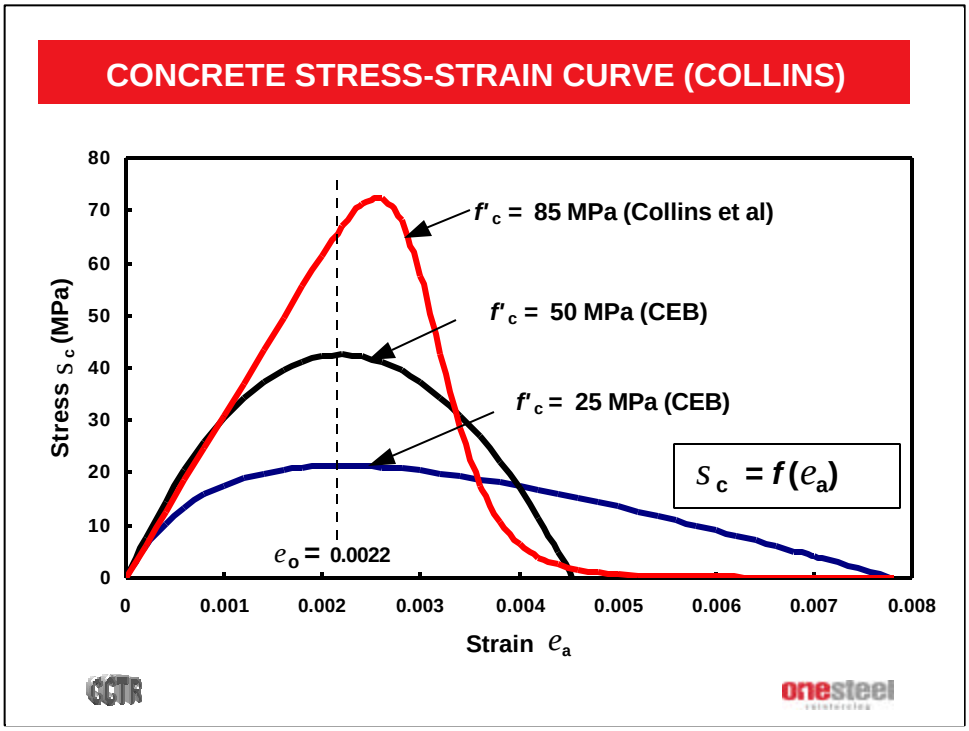
The Australian concrete structures code AS 3600 has previously limited the maximum concrete strength of the concrete to 50 MPa, and an upper limit of 400 MPa on the nominal yield strength of the reinforcement. However, the current standard AS 3600-2001 has increased the maximum concrete strength to 65 MPa and allows the use of 500N grade reinforcement (yield stress 500MPa). In recognition of the industry need and based on current research, the advanced analysis software also enables the use of high strength concrete up to 90 MPa.




To define the concrete stress-strain relationship, the current commentary to the standard recommends the use of the CEB curve when using advanced analysis methods.

One key factor of the CEB curves is that the peak stress occurs at a strain of 0.002 and is independent of the concrete cylinder strength. The unloading behaviour of the varying grades of concrete also differ significantly.

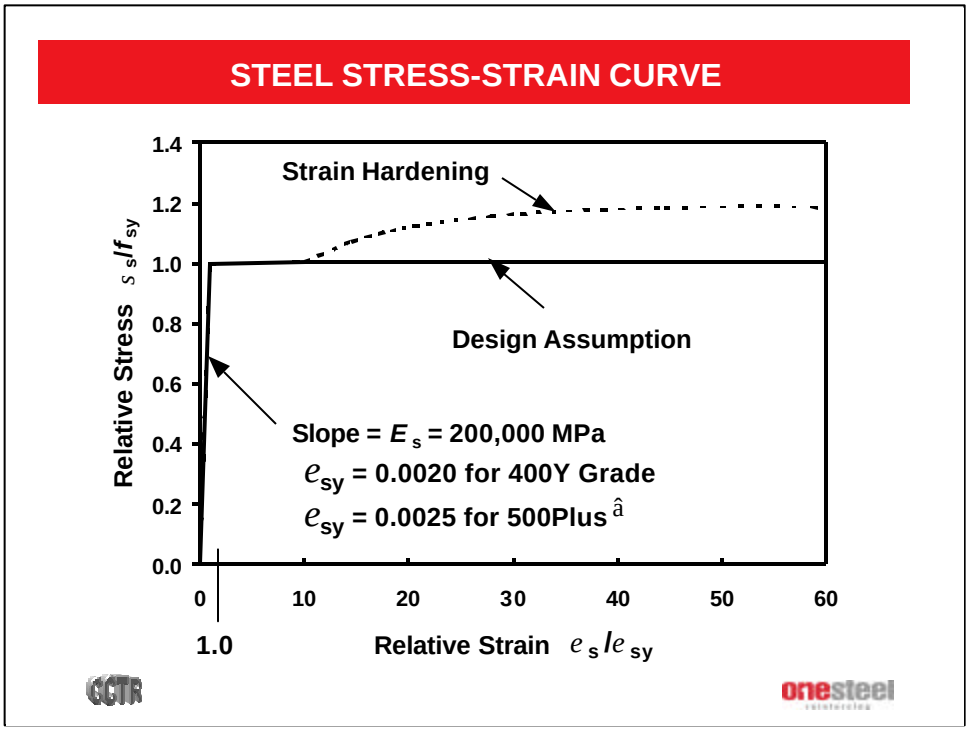
The standard also limits the maximum concrete stress of 85% of the cylinder strength.



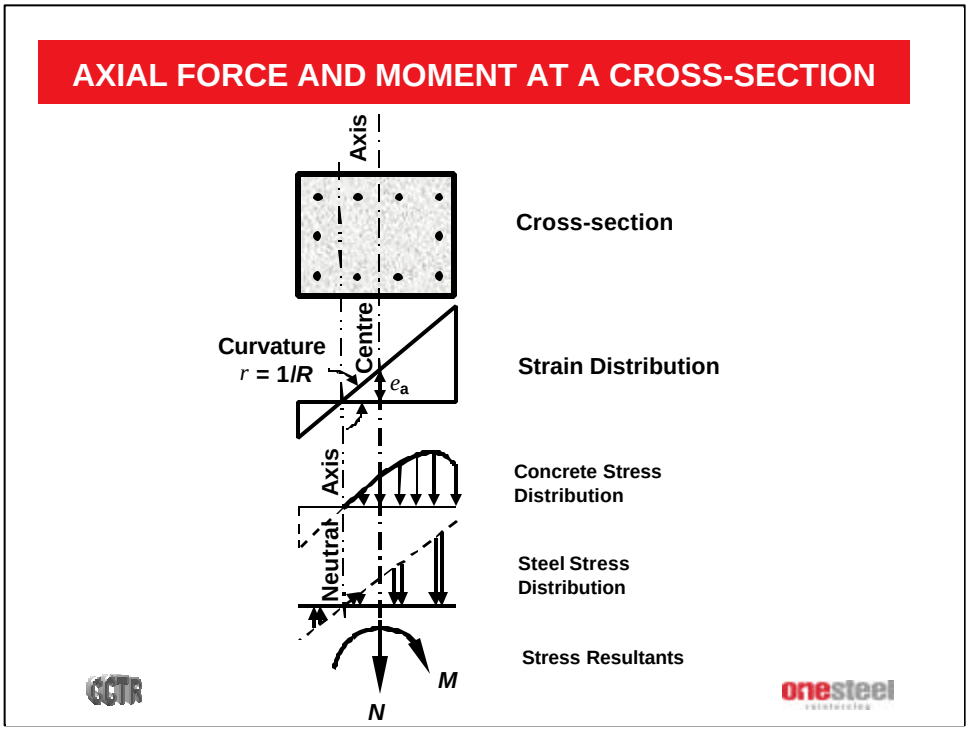

While the CEB curve is considered to be adequate for normal grades of concrete, the authors recommend the use of the Collin's concrete stress-strain curve for high strength concretes.

Unlike the CEB curves, the strain at peak concrete stress is dependent on the concrete cylinder strength.

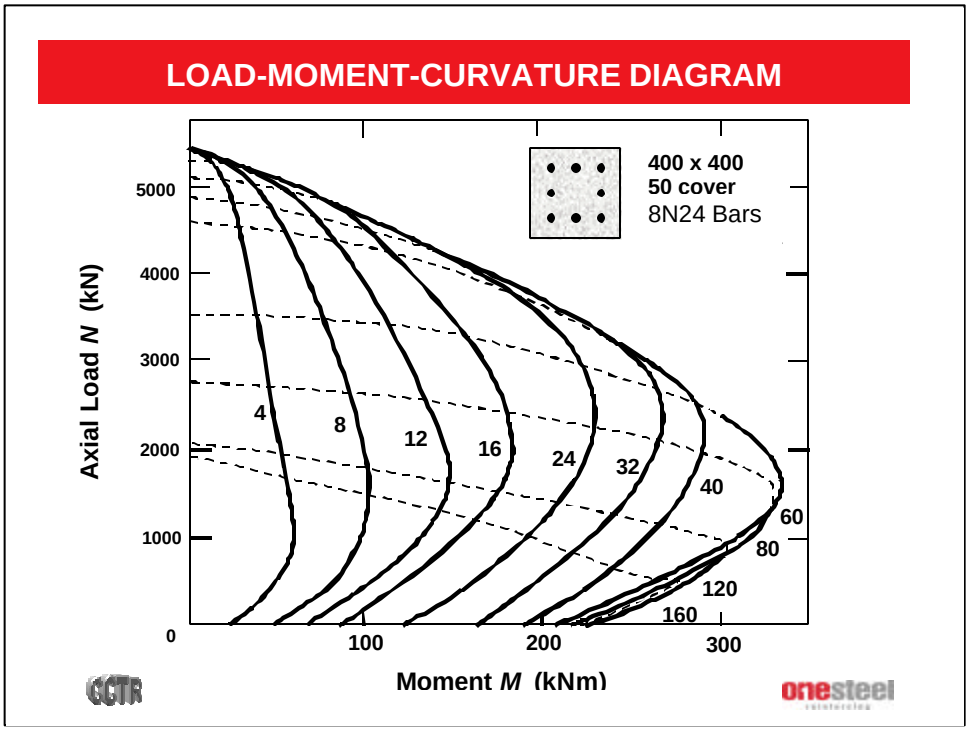
As detailed previously, the maximum concrete stress is limited to 85 % of the cylinder strength




The definition used for the material properties of the steel is the bi-linear elastic plastic stress strain relationship with a linear elastic region to the yield point. The modulus of elasticity for the steel is assumed to be constant at 200,000 MPa. Consequently, the strain at this yield point is assumed to be 0.002 for the 400Y Grade steel and 0.0025 for the 500PLUS® reinforcement. The effects of the strain hardening of the steel are ignored for the advanced analysis of columns.



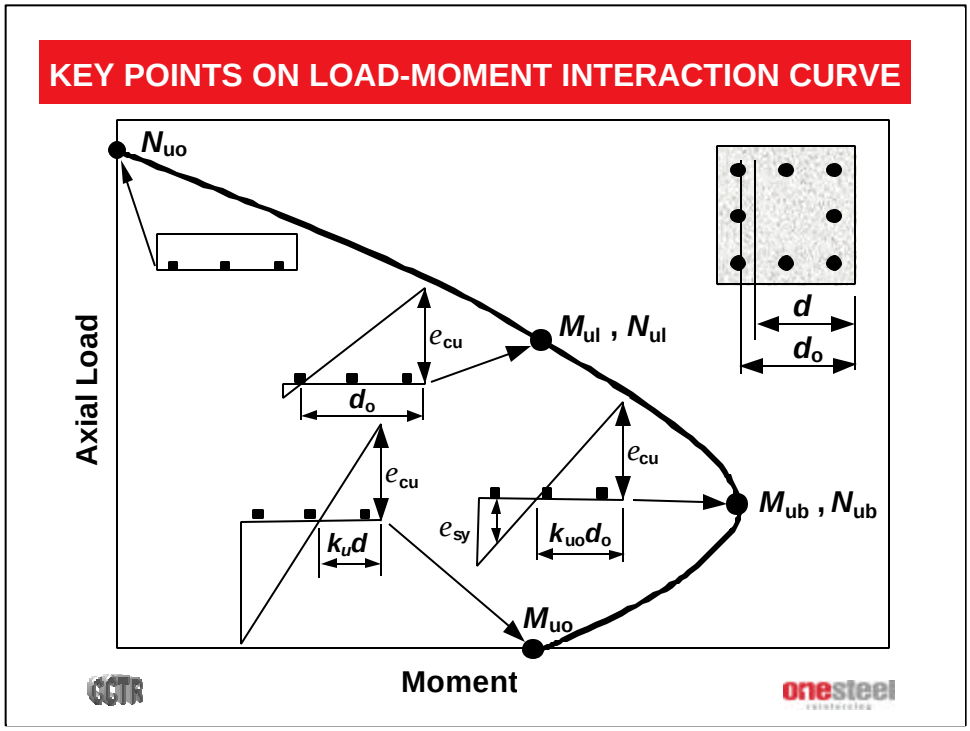

To determine the capacity of a column the assumption that plane sections remain plane is utilised. An assumed strain distribution is applied to the cross-section, defined by the curvature and axial strain at the centroid. From the applied strain distribution and the pre-defined material properties, the stress distribution in the concrete may be determined. The same method is use to determine the stress distribution in the reinforcement. Once the stress distribution is determined, integration is utilised to determine the axial load (*N)* and the moment (*M)* for the given strain distribution.




The load-moment strength interaction diagram is determined by selecting a curvature and varying the applied axial strain. For each value of axial strain, an axial load (*N*) and moment (*M*) is determined and the curve of load-moment values for a given curvature derived. This procedure is repeated for varying values of curvature. Plotting values of load and moment for a constant value of curvature results in the contour chart shown in the slide above. A 3D model of this behaviour shown in next slide, where load (*N*) is on the *y* axis, moment (*M*) on the *x* axis and curvature (ρ) on the *z* axis. Viewing the *x*-*y* axis, then the envelope of (*N*, *M*) values defines the load-moment strength interaction diagram.

## LOAD-MOMENT-CURVATURE DIAGRAM

A 3D model of the load-moment-curvature behaviour of a typical column cross-section is shown above. This was constructed using the contour diagram shown in the previous slide. The lines marked on the model are lines of constant curvature, the vertical axis is the load axis and the horizontal axis is the moment axis.




When using simplified methods or advanced analysis, a number of key points are defined on the load moment strength interaction diagram. These points are used in the determination of the appropriate capacity reduction factors, and include the axial capacity ($N_{uo}$), the bending capacity ($M_{uo}$) and the balance point ($M_{ub}$, $N_{ub}$).

The axial capacity ($N_{uo}$) is the capacity of the section when a constant strain is applied across the cross-section. For 400Y Grade reinforcement this point would always corresponds with the strain at which the peak concrete stress is reached. The pure moment capacity ($M_{uo}$) is the maximum bending capacity of the column with zero axial load. The depth to the neutral axis ($k_{ou}d$) at this point is needed, as it is used as a measure of ductility of the cross-section. The capacity reduction factor ($\phi$) at pure moment is dependent on the value of $k_{uo}$.

As the axial load applied to a column is increased from zero, the moment capacity will increase as applied axial strains relieve some of the tensile strains resulting from the bending. As these compressive strains increase, they will reach a point at which they begin to decrease the bending capacity of the column. This transition point is considered to be the balance point ($M_{ub}$, $N_{ub}$). For rectangular sections, and particularly those that are singly reinforced, this point occurs when the steel on the extreme tensile face begins to yield. When the cross-section is non-rectangular or has multiple layers of reinforcement, the peak moment may not always occur when the reinforcement on the extreme tensile face begins to yield. Using advanced analysis methods, the transition point between applied axial load contributing or degrading the axial capacity is determined accurately.

## CAPACITY REDUCTION FACTOR $f$

**Pure Bending where $N_u = 0$**

$$f_o = 0.8 \quad \text{or} \quad f_o = 0.8\frac{M_{ud}}{M_{uo}} \quad 3 \quad 0.6$$

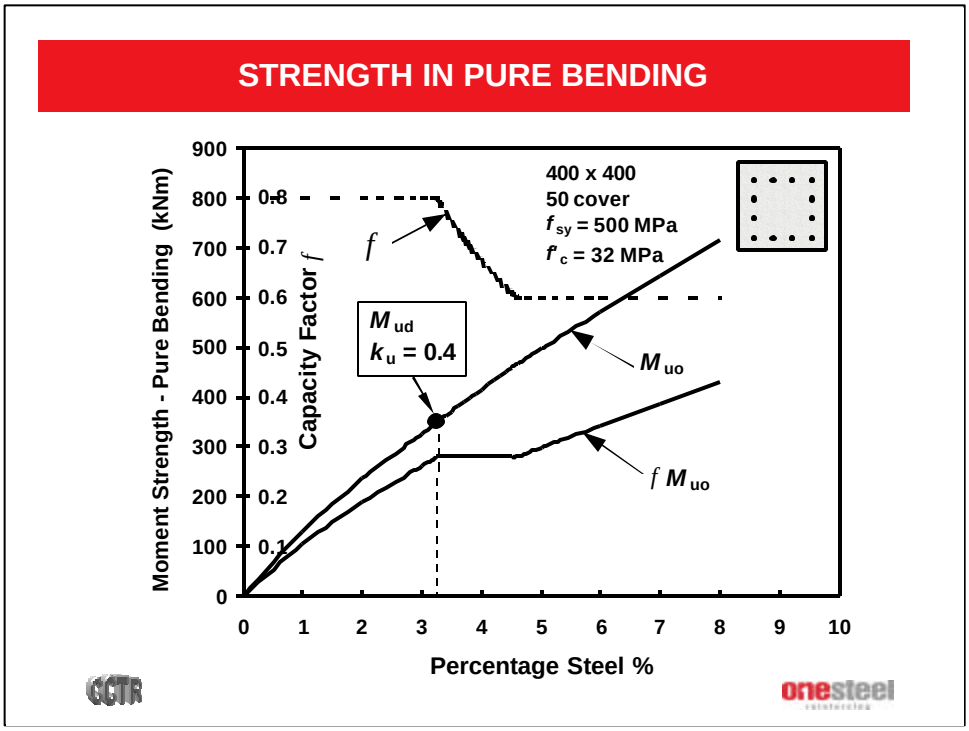
**Combined Bending and Compression where $N_u < N_{ub}$**

$$f = 0.6 + \left[(f_o - 0.6)\left(1 - \frac{N_u}{N_{ub}}\right)\right]$$

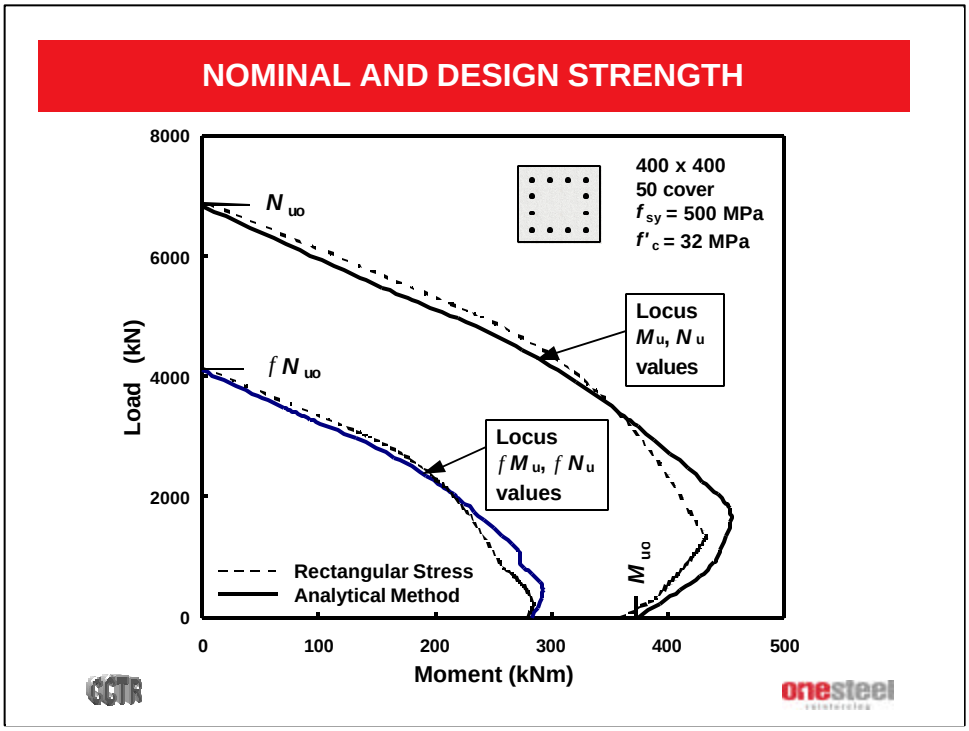
**Combined Bending and Compression where $N_u > N_{ub}$**

$$f = 0.6$$

Capacity reduction factors ($f$), as defined by AS 3600, are dependent on the applied axial load ($N$). When the applied load ($N$) is greater that the axial load at the balance point ($N_{ub}$), the column is considered to be predominantly under axial loading and a reduction factor ($f$) of 0.6 is applied. When the axial load ($N$) is below the balance point ($N_{ub}$), bending is considered to be critical so providing $k_{uo}$ is less than 0.4 the reduction factor ($f$) is varied linearly from 0.6 at the balance point to 0.8 for pure moment.

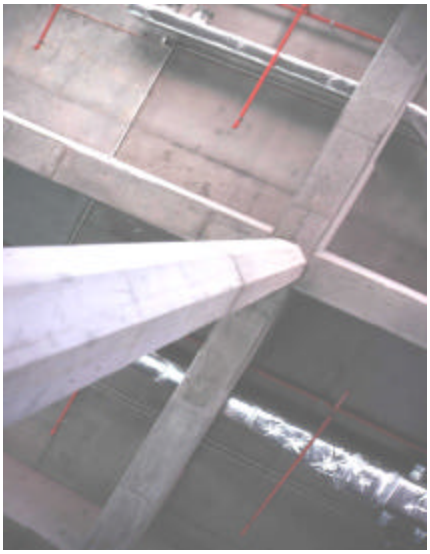



For cross-sections where $k_{uo}$ is greater than 0.4, a reduction factor ($f$) is reduced further to overcome the potential ductility problems. This reduction is based on the assumed moment capacity $M_{ud}$ which is a theoretical moment capacity based on a value of $k_{uo} = 0.4$.

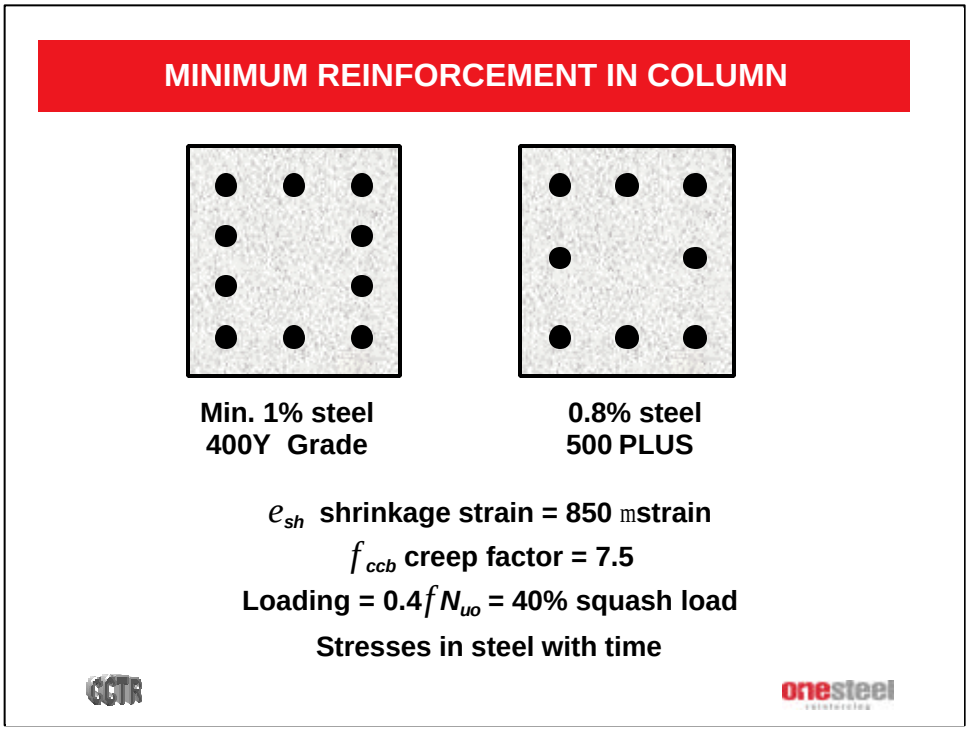



The effect of the reduction factor is very significant on the overall capacities of the cross-section. Thus optimisation using advanced analysis is critical to obtain the best performance permitted for the column. The advanced analysis enables an accurate prediction of the balance point, along with determining the maximum permitted value of $M_{ud}$.

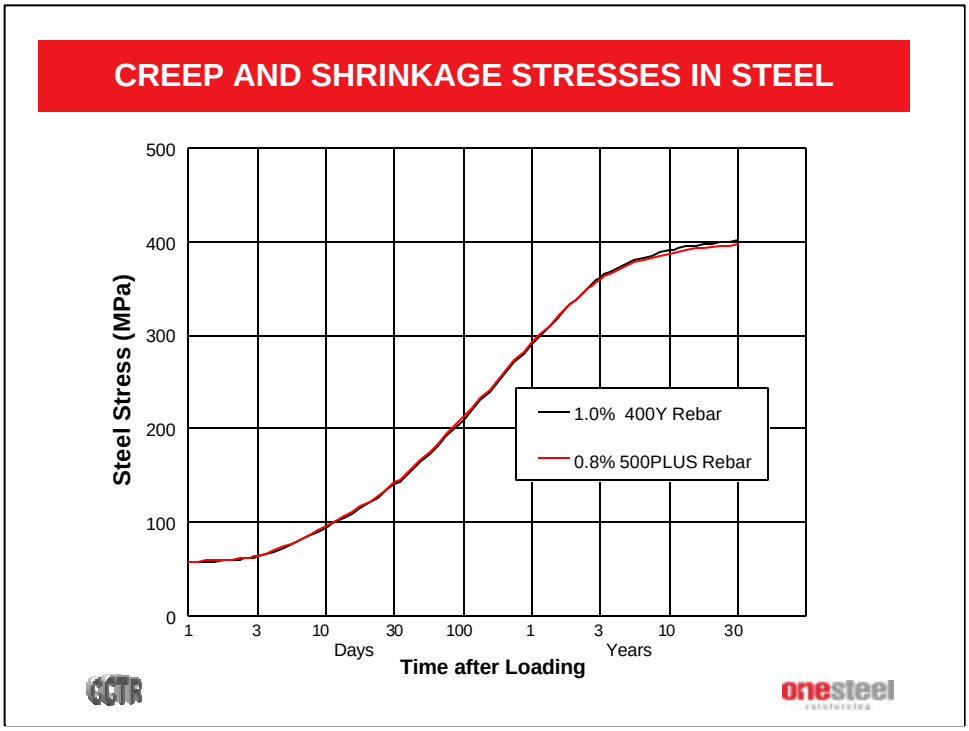
## SLENDER CONCRETE COLUMN



When looking at slender columns, AS 3600 allows the use of moment magnification factors to take into account the effects of slenderness. The software included is only for determining the cross-sectional strength, and thus does not consider slender columns.

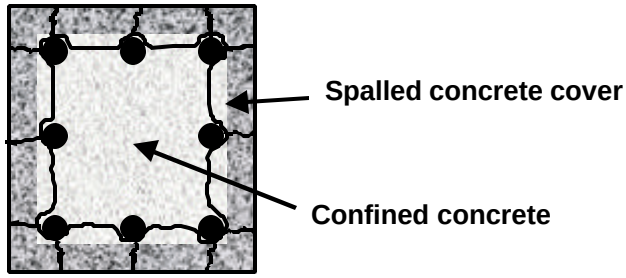



The minimum steel requirements for columns governed by strength as specified by AS 3600 is 1 percent. The commentary to the concrete standard suggests that this limit "guards against yielding of the reinforcement due to shrinkage and to creep under sustained service loading".




Studies have shown that for a column with 1 percent 400Y Grade reinforcement, when compared with an similar column with 0.8 percent 500PLUS® reinforcement and subjected to identical shrinkage strains, the same creep coefficient and supporting the same sustained service load (see previous slide) the stresses in the reinforcement of each column are very similar. Consequently, the advanced analysis will allow the design of columns with less that 1 percent reinforcement for 500PLUS® reinforcement.

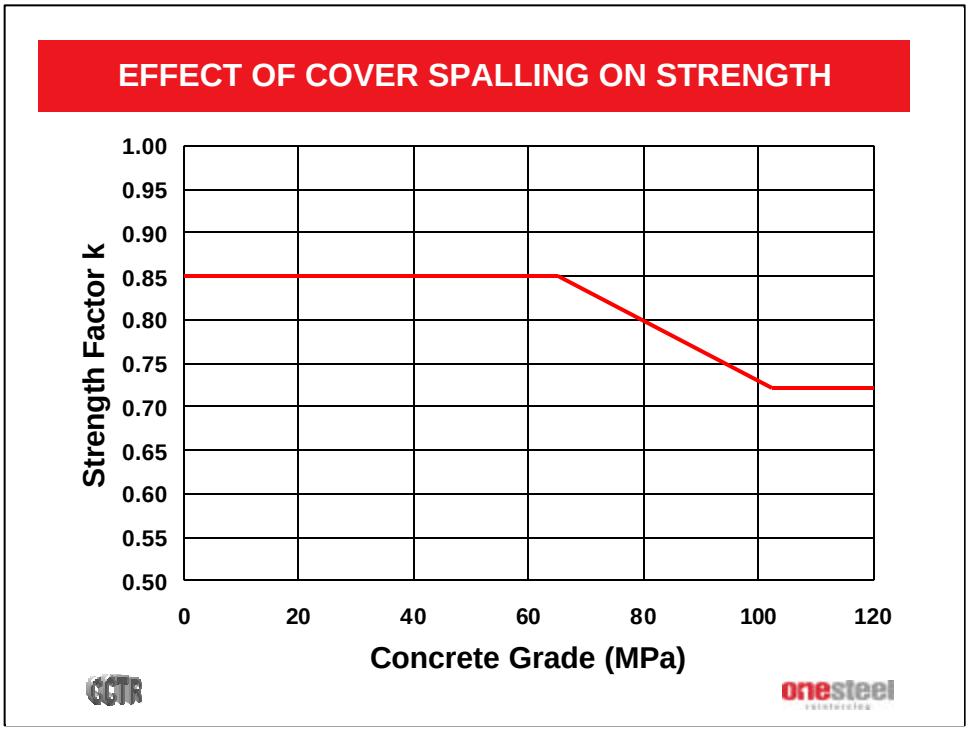
## COVER SPALLING IN HIGH STRENGTH CONCRETE



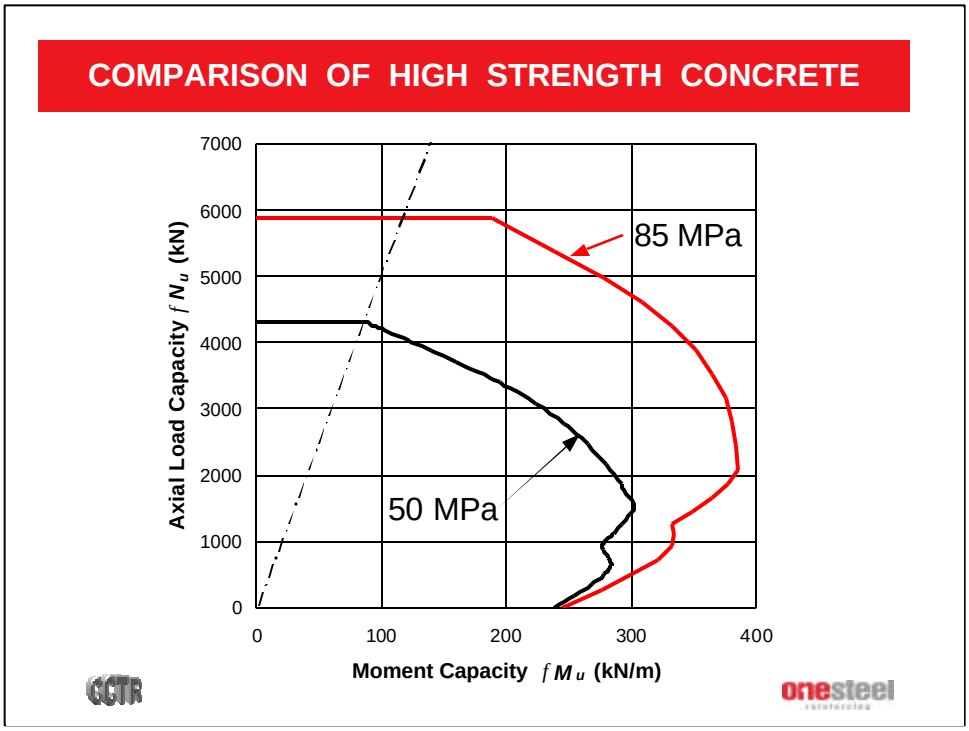

$$N_{uo} = kf'_c A_c + f_{sy} A_s$$

$$\text{For } f'_c \text{ £ } 65 \text{ MPa}, \; k = 0.85$$

The use of concrete grades above those specified in AS 3600 introduce a number of additional problems. A primary consideration is the effect of spalling of the concrete cover on the axial strength of columns.




To overcome the effect of cover spaling, the maximum concrete stress allowed for design is decreased. Numerous experimental studies have demonstrated that for concretes with cylinder strength up to about 65 Mpa, the peak stress reduction factor ($k$) of 0.85 as specified by the standard may be adequate. However, as the concrete cylinder strength moves beyond this point, the peak stress reduction factor should decrease to a lower value. A limit of 0.72 has been suggested in some studies.

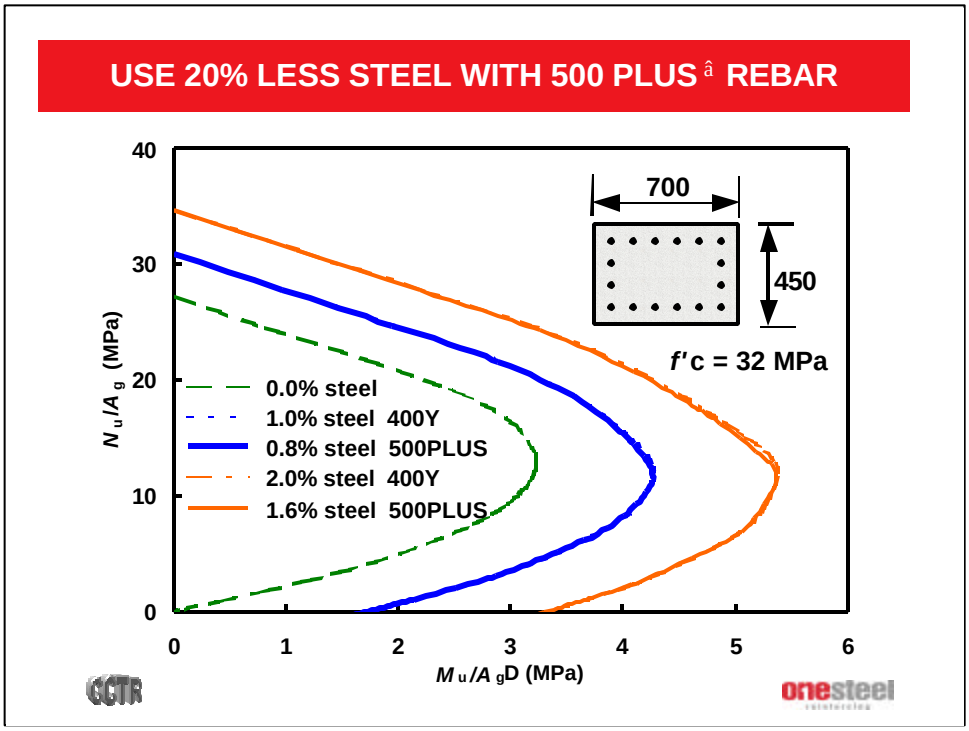



High strength concretes, for a given cross-section, result in an increase in axial load capacity, including the effects of cover spalling, but have an insignificant effect on the pure moment capacity.

When using the high strength concrete the designer should also ensure that the spacing and layout of the confinement reinforcement meet the desired requirements.

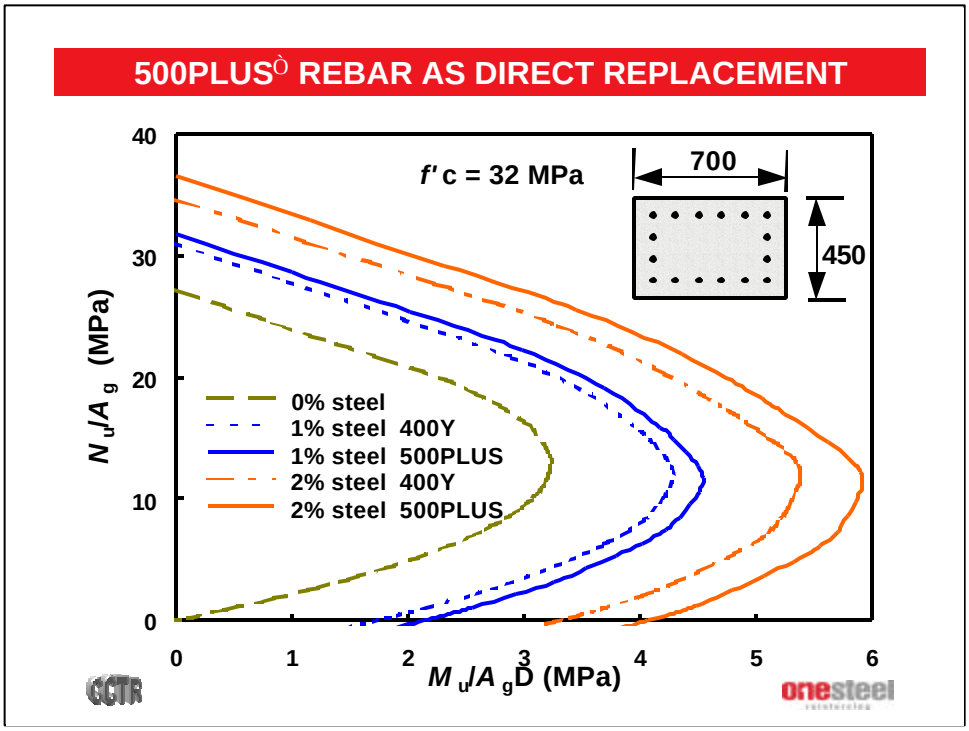
## ADVANTAGES OF ADVANCED DESIGN™ FOR COLUMNS

- Full non-linear material properties
- Numerical integration of stresses for accuracy
- No assumptions for concrete strain at ultimate strength
- High strength concrete HSC included (up to 90 MPa)
- Proper definition of load ($N_{ub}$) balanced point
- Calculation of maximum value of reduced moment $M_{ud}$
- Use of maximum values of capacity reduction factor $f$
- Reduction in value of minimum reinforcement
- Inclusion of effect of spalling of concrete cover for HSC




Comparisons between 400Y grade reinforcement and 500PLUS® reinforcement are demonstrated here.

In the cases shown, a simple replacement of 20 percent less reinforcement results in a similar column behaviour.




Further comparisons between 400Y grade reinforcement and 500PLUS® reinforcement are demonstrated here.

In the cases shown, a simple substitution of the higher grade reinforcement results in an increase in both axial load and moment capacity.

## CONCLUSIONS

- Practice based on supporting research
- Advanced analysis of concrete cross-sections
- Use of high strength concrete
- Advantages of 500PLUS® Rebar
- Accurate software for design
- Ongoing development and research