

# The Effect of Detailing Steel in the Compression Regions of Internal Supports on the Ductility of Reinforced Concrete Beams

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## ABSTRACT

*A clause on detailing in AS 3600 stipulates that 25 percents of the maximum steel in the span of a reinforced concrete beam has to be extended beyond the near face of each internal support. This suggests that the internal support regions have more flexural ductility than the original designed amount. This ductility is obtained indirectly by determining the amount of moment that the support regions are capable of distributing. Non-linear analysis of beams designed and detailed to the design limits specified by AS3600 shows that they have substantial reserve in moment redistribution and load capacity as a result of the inclusion of steel in the compressive zones of the supports. This reserve capacity can be exploited for design and for the strengthening of beams.*

## KEYWORDS

*Strengthening; Ductility; Reinforced concrete*

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## 1 Introduction

This paper describes the result of a theoretical investigation into the reserve ductility presents in the support regions of beams designed and detailed to AS 3600–2001 [1]. This reserve capacity in ductility comes mainly from a detailing requirement stipulated by Clause 8.1.8.4 of AS 3600 that 25 percents of the maximum steel at midspan of a reinforced concrete (RC) beam has to be extended beyond the near face of each internal support. Since beams are normally designed without taking into account of this detailing requirement, the compression steel provided in the regions next to the internal supports enables these regions to have much greater rotational ductility than the original designed amount. The reserve capacity is obtained indirectly by determining the amount of moment the support regions are capable of distributing to the centre region of a span. Any identified reserve flexural ductility at the supports can be utilised either in design, to utilise material efficiently, or in strengthening work, to allow RC beams to support more loads.

## 2 Moment Redistribution

The easiest and most common method to determine structural actions in beams is to use a linear elastic analysis. Recognising the distinct non-linear behaviour of RC structures, the Australian Standard AS3600 allows the bending moment diagram determined using a linear elastic analysis to be adjusted. Usually the support moments are decreased, with a corresponding increase in the span moment to maintain equilibrium of forces in the beam system. This procedure is known as

moment redistribution, and is, in all practical cases, carried out to reduce the amount of steel in the usually congested support regions.

As critical regions in a RC beam have limited ductility, the permissible amount of moment redistribution (MR) depends on the ductility of these regions. AS 3600 [1] specified the MR limit based on the largest  $k_u$ , the neutral axis parameter, of the most critical cross-section in the beam. Ductility of a beam section (or region) reduces with increasing  $k_u$ . Moment redistribution of up to 30 percents can be applied provided that there is adequate beam ductility.

These specified MR limits are from previous research by Ahmad and Warner [2], and they were determined from results obtained from non-linear analyses carried out for beams. These limits are conservative as all the critical regions were assumed to be singly-reinforced. Therefore the beneficial effect on flexural ductility and MR from the presence of detailing steel in the compressive regions was not included in that research.

It should be noted that in the present study, the allowable moment redistribution is assumed to depend on the  $k_u$  at the support and not the maximum value in the beams, even though in some beams the  $k_u$  at midspan is larger. This is not in accordance with AS 3600 but was considered an acceptable assumption for the beams studied, as the main demand for ductility occurs in the support regions, not in the midspan region.

### 3 Test Beams

Broad ranges of practical beams were chosen for analysis. All beams were designed with N32 concrete (characteristic strength  $f'_c=32$  MPa with a mean strength  $f'_{cm}=37.5$  MPa) and 500N steel ( $f_{sy}=500$  MPa with a mean strength  $f_{sm}=575$  MPa). Concrete cover to the centroid of steel was 50mm. All beams were single span with their ends fixed. They represent, approximately, the internal spans of a continuous beam. All beams were loaded with a uniform distributed load, with dead load equal to live load.

The main variables of these beams were cross-section size,  $k_u$  value at the support regions and  $L/D$  ( $L$ =length and  $D$ =overall depth) ratio.

Their cross-sections (width by depth) were:

- 300mm x 600mm
- 400mm x 800mm
- 400mm x 1200mm
- 500mm x 500mm

Three  $L/D$  ratios of beams were chosen. The first two had fixed values, and the last varied. The three ratios were:

- $L/D = 10$
- $L/D = 20$
- maximum  $L/D$  that satisfied deflection requirement

The last ratio above was determined by a process of elimination during the design/analysis process. This ratio was included as preliminary runs carried out during the present study showed that an increase in  $L/D$  caused a decrease in MR for a beam with all other variables fixed. Hence, for each combination of beam cross-section and  $k_u$  at the supports, the  $L/D$  of the beam was progressively increased in steps. This ratio was increased by increasing the latest  $L$  value by  $2D$  at the start of each step. For each step, the bottom steel at midspan was increased until ductility limit at the support region was reached. The beam was then checked to determine whether it satisfied the deflection limit as described in Section 5 below. If the beam met the deflection limit, its  $L/D$  was increased and the step repeated until a step was reached where the beam no longer satisfied the deflection limit state. When this occurred, the  $L/D$  of the previous step was chosen as the maximum  $L/D$  that satisfied the deflection requirement.

Four  $k_u$  values at the support regions, ranging from 0.1 to 0.4 with an increment of 0.1 were used.

#### **4 Detailing of Reinforcement in Test Beams**

For each set of beams with fixed chosen values of cross-section,  $L/D$  ratio (this value was not fixed for the case of varied  $L/D$ ) and support  $k_u$ , the five different beam details selected for analysis were:

- theoretical design steel (Detail 1)
- detailed in accordance with AS3600 (Detail 2)
- theoretical design steel –increase centre tensile steel (Detail 3)
- detailed in accordance with AS3600 –increase centre steel, repair scenario (Detail 4)
- detailed in accordance with AS3600 – increase centre steel with 25 percents of steel extended into the internal supports, non-linear design scenario (Detail 5)

Details 1 through 5 are shown in Figure 1.

##### **Detail 1: theoretical design beam**

This detail is for the beams as designed, that is with only tensile reinforcement included at the supports and at the centre of the beam. While this detail is not in accordance with AS3600 requirements, it did satisfy AS3600 strength requirements and represented the theoretical design beams, prior to detailing to AS3600.

##### **Detail 2: detail in accordance with AS3600**

This detail had the same amount of tensile steel as detail 1, but it was in accordance with AS3600. It had 25 percents of the maximum tensile steel at the centre of each beam extended into its supports and one-third of the tensile steel at the support extended for the entire length of the beam. The beam reinforcement detailing represented the usual ‘as constructed’ beam (except for shear reinforcement, which is not part of the present study).

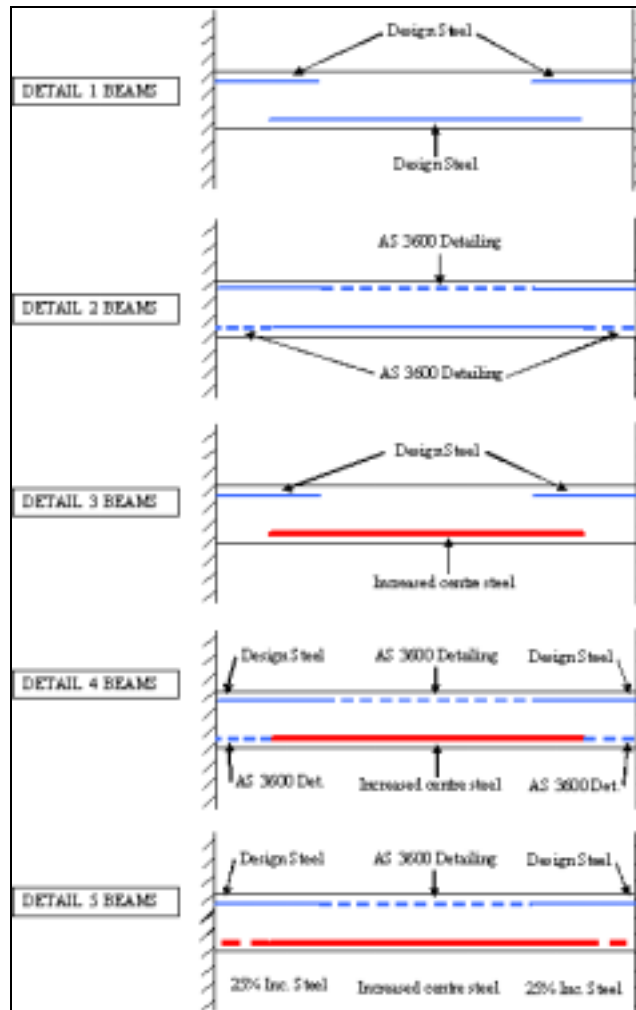


Figure 1: Moment redistribution plots for  $L/D = 10$ , details 3 & 4 beams

**Detail 3: theoretical design steel –increase centre tensile steel**

This detail was selected to enable the determination of the ductility of the support regions of the theoretical design beam. The centre tensile steel was increased until the support regions failed. The non-linear analysis of this beam provides an indication of the support ductility of the theoretical beam and conservativeness of the current AS3600 MR limits.

**Detail 4: detailed in accordance with AS3600- increase centre steel, repair scenario**

This detail was selected to enable the actual ductility of the support regions of a beam detailed to AS3600 to be determined. The support tensile steel (including the one-third area extension across the length of the beam) and steel located in the compression zone of the support (the 25 percents extended from the centre of the beam), were as per AS3600 requirements. The tensile steel in the centre of the beam was then progressively increased until the beam reached its deflection and/or strength limits. This beam represents a repair scenario where an existing beam has to be strengthened and additional steel cannot be added to the bottom regions of the internal supports, which is common.

**Detail 5: detailed in accordance with AS3600- increase centre steel with 25 percents of the steel extended into the internal support (non-linear design scenario)**

This detail was selected to enable the ductility of the support regions of a beam designed and detailed to the requirements of AS3600, and subjected to an increase of the centre steel, together with a corresponding increase of 25 percents of this steel in the support regions, to be determined. The support tensile steel (including the one-third area extension across the length of the beam), designed as per AS3600 requirements, was kept constant. This detail is different from Detail 4 as the ductility of the support regions increases as the centre bottom steel increases. This is caused by the extension of 25 percents of this steel into the compression regions of the supports.

**5 Deflection Limit**

Where a deflection check was carried out, the serviceability requirement was based on a simplified approach given in Clause 8.5.3 of AS3600, but a more accurate short-term deflection determined using the load-deflection relation from the non-linear analysis. The total load was determined using the design load of the beam  $w^*$ , and the short-term  $\psi_s$  multiplier and long-term multiplier  $\psi_l$  of AS/NZS 1170.0 [3]. For this study the short-term multiplier  $\psi_s$  is 0.7 and the long-term multiplier is 0.4, values suitable for residential houses, shops and car parks. The deflection limit under total load was chosen as  $L/250$ .

**6 Non-linear Analysis**

A non-linear analysis program [4] was used to obtain the behaviour of the beams under proportional loading. This program uses a segmental approach in which the beam is divided into line elements, and these elements are further divided into segments. For the present study, the length of segments is chosen to be the same as the depth of the section. The analysis is carried out using a curvature-control procedure, whereby a critical key-segment is chosen, and the load scaling factor and the action effects of the beam system are obtained for progressively increasing curvature of this key segment. The analysis requires the "unit" load pattern to be defined. At the end of each curvature step, a scaling factor is obtained.

For the non-linear analysis, the non-linear stress strain relationship of concrete was as described in the paper by Wong et al [4]. The steel reinforcement was elastic plastic. Mean material properties values were used. Tension stiffening was not included in the analysis. Failure was assumed to occur when the ductility of the region (or section) was exhausted

**Beams with details 1 and 2**

In the analysis of beams with details 1 and 2, the amount of steel was already predetermined and was not changed during analysis. Therefore the simplified steps given below were used to analyse a typical beam:

- A non-linear analysis was carried out to give the behaviour of the beam.
- A check was conducted to ensure that the midspan and support tensile steels had yielded, as expected for all details 1 and 2 beams.
- The values of the uniform distributed load,  $w_u$ , and the support and midspan moments at failure were noted.

The analysis of these beams was to confirm that the designed moment redistribution of these beams was achieved. The difference between the design values and their corresponding values from analysis was found to be negligible.

### Beams with details 3, 4 and 5

For these beams, the bottom steels were increased during the analysis. Increasing the steel at midspan of the beam not only increased the moment capacity of this region, but also increased the flexural stiffness. For detail 5 beams, the ductility of the support regions was also increased as a result of extending 25 percents of the mid-span steel into the supports.

There was a limit to the amount the midspan steel can be increased. This limit was governed by one of the limits listed below:

- Support failure limit – the support failed before the centre steel yielded. This occurred for supports with limited ductility.
- AS3600  $k_u$  of 0.4 limit – the strength at midspan of the beam was limited by the amount of steel allowed by AS3600.
- Deflection limit – the beam might have the capacity to allow for a further increase in midspan steel, but the deflection limit was exceeded. This limit was checked for details 4 and 5 beams with varied  $L/D$  only.

## 7 Effect of Compression Steel on Support Ductility for Beams with Fixed $L/D$ Ratio

Maximum MR versus  $k_u$  plots for details 3 and 4 beams with fixed  $L/D$  ratios are shown in Figures 3 and 4. These figures show that both set of beams generally have substantial reserve ductility when compared with the design ductility. Deflection limits were not checked for the fixed  $L/D$  ratio beams. Comparison between the MR of detail 3 beams and detail 4 beams shows that the additional ductility due to the provision of compression steel is generally greater for beams with larger  $L/D$  ratio and  $k_u$ . Results from these beams also show that MR is quite independent of beam depth, or width to depth ratio.

Figure 3 shows that there is no gain in ductility between detail 3 and detail 4 beams with  $k_u$  less than about 0.225. For beams in this region, ductility of the support regions was artificially restricted by the limit of midspan  $k_u$  to 0.4.

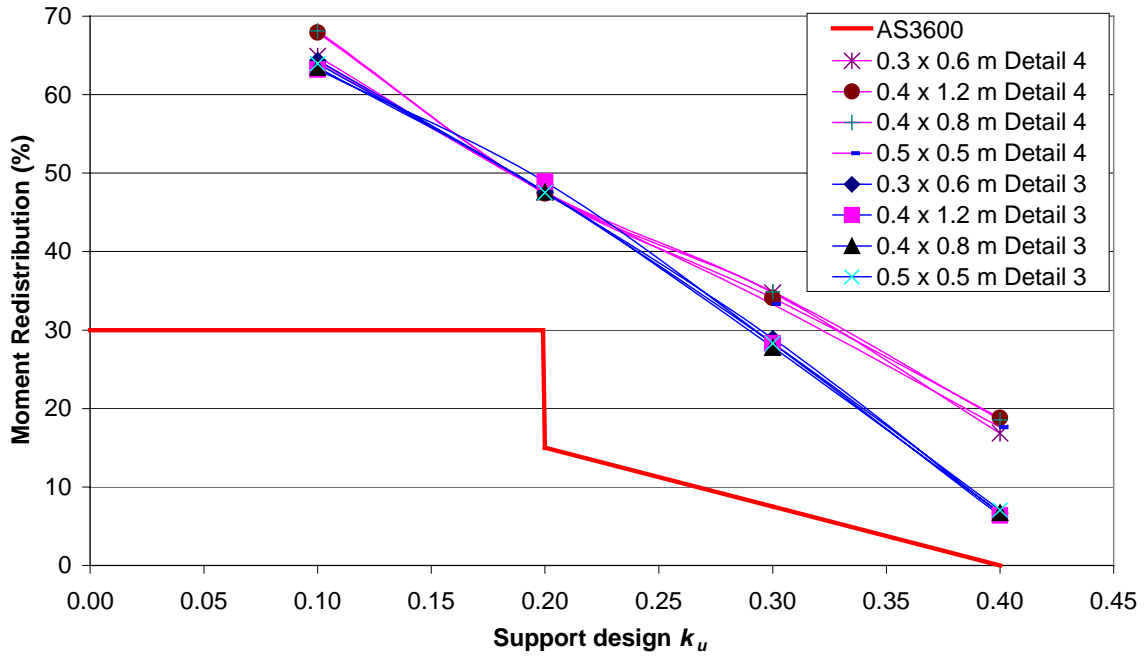


Figure 3: Moment redistribution plots for  $L/D = 10$ , details 3 & 4 beams

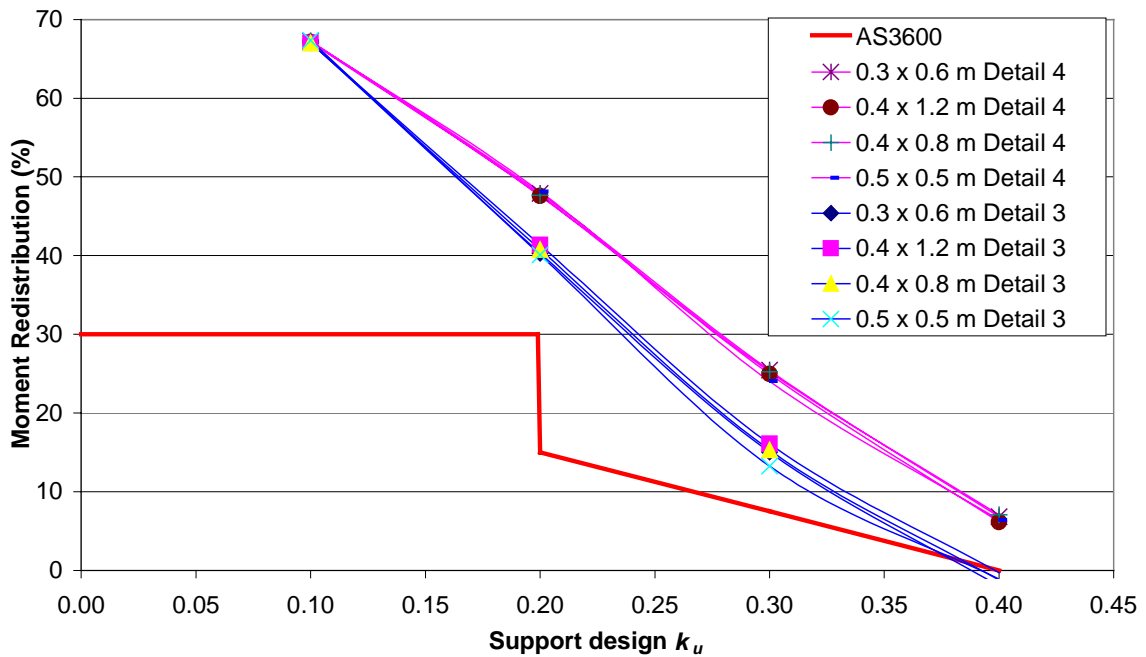


Figure 4: Moment redistribution plots for  $L/D = 20$ , details 3 & 4 beams

## 8 Effect of Compression Steel on Load Capacity of Fixed $L/D$ Beams

An increase in midspan steel, due to the exploitation of reserve support ductility, allows a greater magnitude of load to be supported by beams. Curves for the percentage increase in load versus support  $k_u$  are shown in figures 5 and 6 for detail 3 and 4 beams respectively. The percentage increase in load for each beam is relative to the load of the corresponding beam with detail 1, the theoretical design beam. The maximum increase in load is approximately 22 percents (at  $k_u=0.20$  and  $L/D=20$ ) of that obtained for the theoretical design beam.

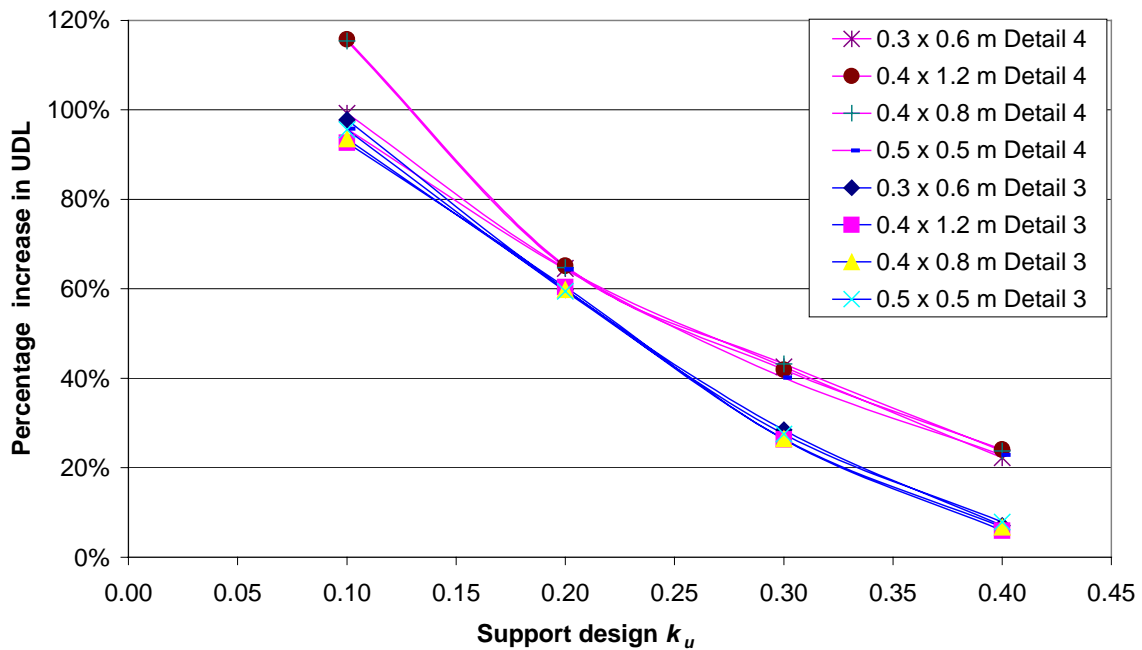


Figure 5: Increase in load at failure:  $L/D = 10$

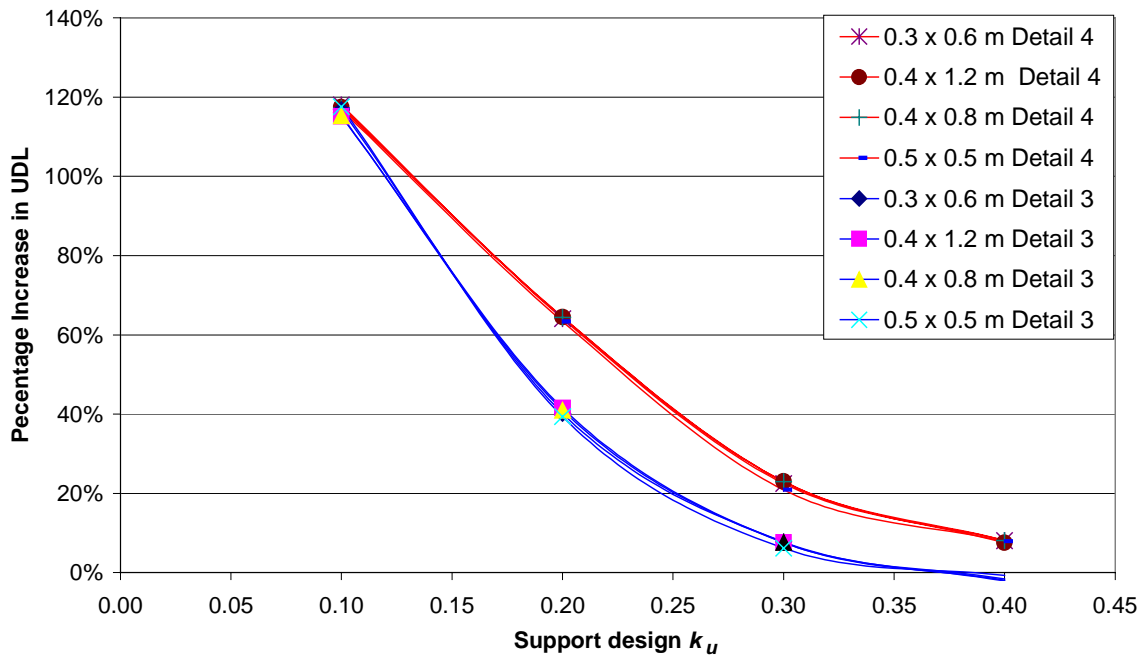


Figure 6: Increase in load at failure:  $L/D = 20$



## 9 Effect of Compression Steel on Support Ductility

In Section 8, detail 4 beams represented the investigation into the reserve ductility of the internal support regions of fixed L/D beams detailed to AS3600, where the steels in the support regions remained as originally detailed. This represents a repair situation where the bottom compression steel at the support cannot be increased. Additional beams were analysed that had the same details as these beams but with their L/D values varied until they reached the limit of the total allowable deflection. The ductility limits for these additional detail 4 beams are shown in Figure 7.

The extra support compression steel placed during the detailing of a RC beam is normally not taken into consideration in design. The present design methodology in AS3600 cannot exploit the increased ductility of the internal supports from this steel. However, if a non-linear design approach [5] is used, than this ductility can be taken into consideration during design. Further beams were analysed, namely detail 5 beams, to investigate the ductility limits in a non-linear design scenario. These beams also had their L/D adjusted until the total deflection limit was reached. The ductility limits for detail 5 beams are also shown in Figure 7.

Figure 7 shows that the ductility allowed by AS3600 is very conservative for most beams designed in practice. At  $k_u = 0.2$ , the allowable MR is 15 percents; the MR the support is capable of achieving, is about 46 percents, an increase of 31 percents. This increase, however, decreases almost linearly to about 18.5 percents at  $k_u = 0.3$  and dropping to zero at  $k_u = 0.4$ . The difference is still important as most beams designed in practice have a  $k_u$  of less than 0.3.

The results also show that once the artificial limit of the midspan  $k_u$  of 0.4 is overcome, the benefit of the non-linear design scenario over the repair scenario is apparent as can be seen in the bottom half of the curves.

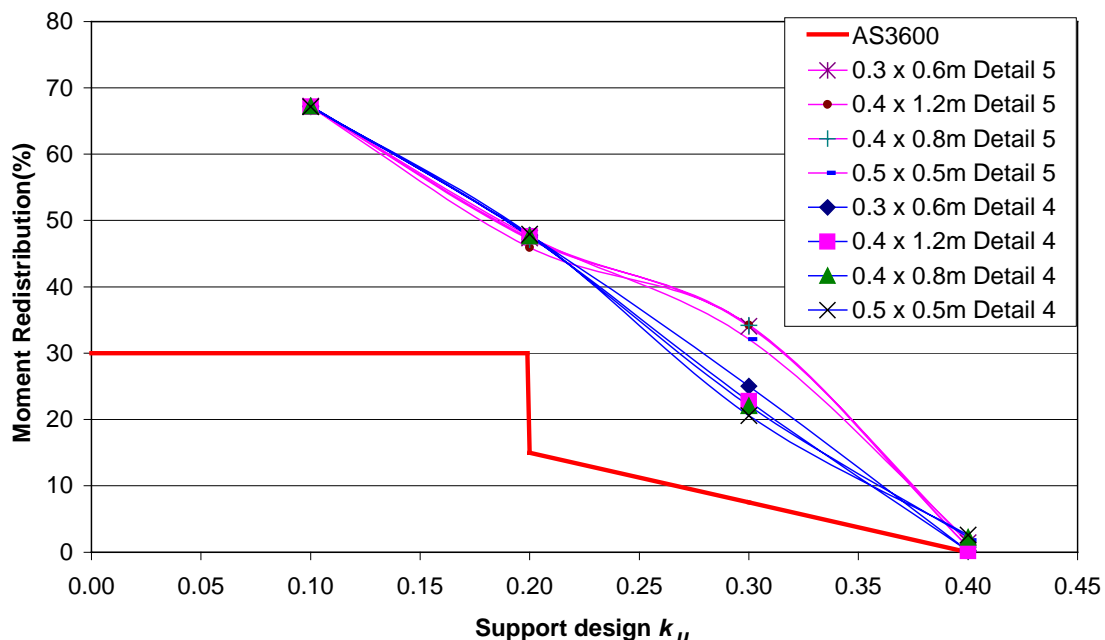


Figure 7: Allowable MR for details 4 and 5 beams with largest L/D and met AS3600 deflection limits

## 10 Concluding Remarks

The increase flexural ductility in the internal support regions due to compression steel from detailing has been found to be substantial. This present study has shown that, theoretically, the current detailing requirements of AS 3600 results in greater ductility of the support regions than their designed value, and this reserve ductility can be favourably exploited for both strengthening work carried out on existing beams and for non-linear design of new beams. However, to get maximum benefits from the presence of the detailing steel, a non-linear design methodology has to be used.

While the present study was mainly concerned with the investigation of the effect of detailing steel on ductility, results obtained show that, generally, the present ductility limits of AS3600 are very conservative for most practical beams.

## 11 References

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