Challenging the limits for beam bending designs

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Challenging the limits for beam bending designs

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ABSTRACT
The traditional design limits of beams in bending have been challenged by testing from very under-reinforced design to over-reinforced and strengthened over-reinforced designs in order to investigate if the current limits could be abolished. The ductility of normally reinforced beam depends significantly on the amount of reinforcement and an over-reinforced design can be modified to behave as a normally reinforced design, but with extreme ductile behaviours, but may requires stirrups beyond the codes requirements for columns. The ductility of under-reinforced beams may exceed that of some normally reinforced designs.

Key words: Modelling, Reinforcement, Structural Design, Testing.

1. INTRODUCTION

The traditional beam designs use normally reinforced cross-sections, in order to have a good warning before failure, a ductile and plastic behaviour near the peak load and at the same time achieve a good economy in the design, since such a design utilizes the reinforcement (the most expensive material) to its full capacity. The normally reinforced cross-section is defined as the tensile reinforcement yielding, but not rupturing before the beams failure (peak load):

$$\varepsilon_y \leq \varepsilon_s \leq \varepsilon_u$$

The reinforcement strains are here defined as

ε_s tensile strain,
ε_y yield strain,
ε_u ultimate tensile strain capacity.

The design of prefabricated elements requires, however, often very low height of build-in beams in wall elements (e.g. over window and door holes), but requires at the same time a high strength and a high stiffness. This is not always possible with a normally reinforced beam.

In other designs, there is plenty of height for the beams and the minimum reinforcement, required for achieving the normally reinforced state, leads to a capacity well beyond the required. It would be of high interest to explore the possibility to actually only use the reinforcement, required for obtaining the necessary loadcarrying capacity and the required stiffness.

It was therefore decided to look into the effects of the reinforcement degrees on the beam behaviours in two projects, with help from the prefab producer EXPAN/CRH, who would produce and deliver the beams and relevant samples to DTU for testing.

2. TEST PROGRAM

The first project [1] designed and tested a number of beams (see Table 1) starting with normally reinforced beams and increasing the tensile reinforcement until the over-reinforced cross-section was reached. The theory predicted that an increase of the compressive reinforcement in an over-reinforced cross-section should change the design back to a normally reinforced cross-section. The project has an initial test program (beam A to H) and later a second, additional program (beam K to M).

The second project [2] designed and tested beams N to U (see Table 1), starting from with the normally reinforced cross-section (where beam design N and A should be as identical as possible) and decreasing the reinforcement or increasing the cross-section until a seriously under-reinforced cross-section was obtained.

Table 1 – Test programs [1],[2]. No is number of beams, dimensions are in mm and strengths in MPa. Note NR denotes normally reinforced cross-section, OR over-reinforced, NR normally reinforced due to the effect of additional compressive reinforcement and UR under-reinforced.*

			Comp. reinf.		Tensile reinf.		Stirrups	Design			
Ref	Serie	No	Area	f_{ym}/f_{um}	Area	f_{ym}/f_{um}	Ø/s	Width	Height	f_{cm}	Note
[1]	A	2	2Ø8	564/690	2Ø12	600/694	Ø8/100	200	200	43	NR
[1]	B	3	2Ø8	564/690	2Ø16	584/670	Ø8/100	200	200	43	NR
[1]	C	2	2Ø8	564/690	2Ø20	585/666	Ø8/100	200	200	43	NR
[1]	D	2	2Ø8	564/690	3Ø20	585/666	Ø8/100	200	200	43	NR
[1]	E	2	2Ø8	564/690	4Ø20	585/666	Ø8/100	200	200	43	OR
[1]	F	3	2Ø12	600/694	4Ø20	585/666	Ø8/100	200	200	43	OR
[1]	G	2	2Ø16	600/694	4Ø20	585/666	Ø8/100	200	200	43	NR*
[1]	H	2	2Ø20	585/666	4Ø20	585/666	Ø8/100	200	200	43	NR*
[1]	K	3	2Ø8	564/690	3Ø25	543/668	Ø8/50	200	200	34	OR
[1]	L	3	2Ø25	543/668	3Ø25	543/668	Ø8/50	200	200	34	NR*
[1]	M	3	4Ø25	543/668	3Ø25	543/668	Ø8/50	200	200	34	NR*
[2]	N	3	2Ø8	552/700	2Ø12	586/679	Ø8/100	200	200	55	NR
[2]	O	2	2Ø8	552/700	2Ø10	630/714	Ø8/100	200	200	55	NR
[2]	P	2	2Ø8	552/700	2Ø8	552/700	Ø8/100	200	200	55	NR
[2]	Q	2	2Ø8	552/700	2Ø8	552/700	Ø8/100	200	300	55	NR
[2]	R	2	2Ø8	552/700	2Ø8	552/700	Ø8/100	200	400	55	UR
[2]	S	2	2Ø8	552/700	2Ø8	552/700	Ø8/100	250	400	55	UR
[2]	T	2	2Ø8	552/700	2Ø8	552/700	Ø8/100	300	400	55	UR
[2]	U	2	2Ø8	552/700	2Ø8	552/700	Ø8/100	350	450	55	UR

A total of 44 beams were produced by EXPAN/CRH in three steps and delivered to DTU Civil Engineering along with samples of the longitudinal reinforcement types and concrete cylinders.

3. RESULTS.

All beams were tested in four-point bending (see Figure 1), with registration of loads, deformations and crack distribution and also videorecording of all tests (available at Youtube [3]). All longitudinal reinforcement types and concrete cylinders from the three productions were tested as well and their average strengths listed in Table 1.

Figure 1 – Test setup with beam Q2 after failure [2].

It was observed [1] during testing of designs A to H, that the ductility of the cross-sections (see Figure 2) was less than what would have been expected from the theory and that it varied a lot within the range of the normally reinforced beams. Over-reinforced beams were, as expected, less ductile, but the attempt to increase the compressive reinforcement in beams G and H was not successful. This may have been due to the buckling of the compressive reinforcement, where the stirrups had been placed with 100 mm distance, sufficient for the design of a column.

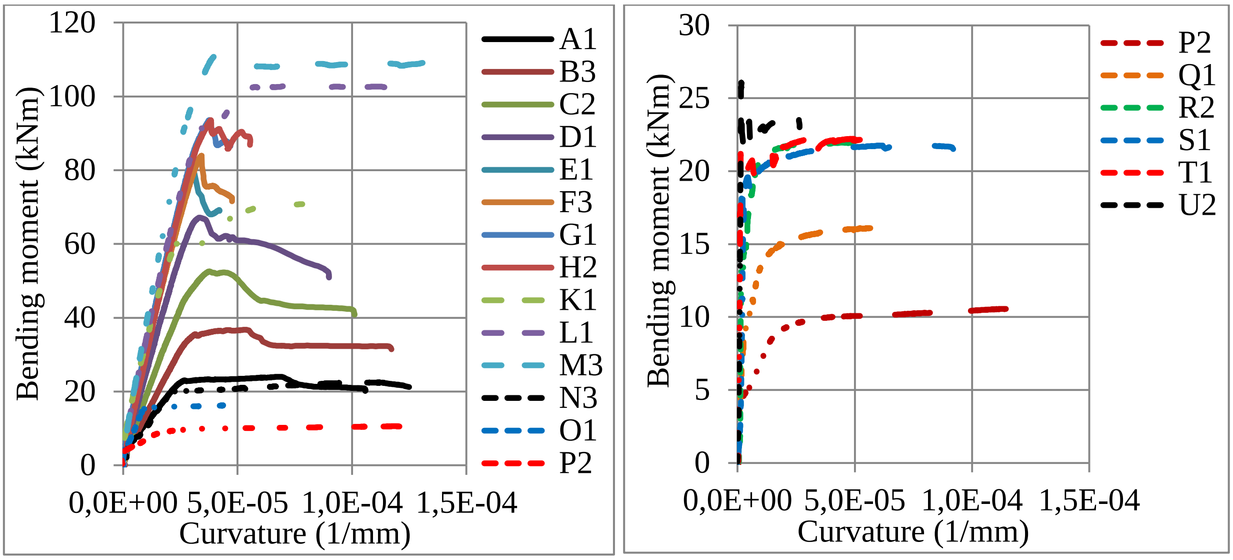

Figure 2– Representative bending moment-curvature curves for beams with constant cross-section 200 x 200 mm (left) and with varying cross-section (right).

The second part doubled therefore the number of stirrups and increased the compressive reinforcement in some designs, after which very good ductility and strength was, partly due to a confinement effect of the reinforcement. The ductility was at least equal to the ductility of a normally reinforced cross-section and the testing even had to be stopped before failure, due to the large deformations.

The second project [2] showed that the ductility of a number of the under-reinforced designs was as good or better than that of the normally reinforced designs near the upper reinforcement limit. The most under-reinforced designs had as predicted a bending moment capacity of the cracked cross-section below the uncracked cross-section, but the only slightly under-reinforced cross-sections actually had signs of a plastic plateau and a reserve after cracking (see Figure 2).

4. CONCLUSIONS

The ductility in a cross-section depends significantly on the reinforcement degree, even for normally reinforced designs.

Over-reinforced designs can be changed back to normally reinforced designs by adding compressive reinforcement, however, the design must then consider the possible buckling of the compressive reinforcement, which may require additional amount of stirrups beyond the codes requirements for stirrups for columns.

Over-reinforced designs can be changed back to normally-reinforced designs, by adding additional compressive reinforcement, however, this may require stirrups beyond the codes requirements. Such designs should at the moment be verified by testing.

Under-reinforced designs may have a ductile behaviour, however, the designer must for some of these designs distinguish between designs, where the beams is exposed to a forced deformation and those where it is exposed to an increased moment.

Under-reinforced designs should only be used after serious considerations, as their cracked capacity may be below the uncracked capacity (see Figure 2), but similar problems with the moment-curvature relation can be observed for normally reinforced cross-sections near the limit for over-reinforced designs.

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