EFFECT OF COMPRESSIVE STRENGTH AND REINFORCEMENT RATIO ON STRENGTHENED BEAM WITH EXTERNAL STEEL PLATE

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Abstract:

The present study is an experimental comparison between the effect of increasing the compressive strength of the section and increasing the reinforcement ratio on the results of strengthening reinforced concrete beams with external steel plates of constant dimensions.
The experimental program consists of testing ten reinforced concrete beams. Five of them are without external steel plates to be the original specimens while the other five ones are provided with steel plates of same dimensions glued at the bottom face of the beams.
Three values of compressive strength (f'c) were used in this study which were (22, 45 and 71MPa) and also three ratios of internal reinforcement (ρ) which were (0.01411, 0.02116 and 0.03445) to investigate their effects on the strengthened beams behavior.
The results showed that the cracking load and the ultimate load can be increased up to (150% and 137%) respectively. Also, by increasing the section compressive strength all the properties of the strengthened beam can be improved while by increasing the reinforcement ratio the deflection and cracking can be reduced to improve the elastic behavior of the beam.

Keywords: Strengthened beam, external plate, deflection ductility, restraining.

تاثير قوى الشد القصوى ونسبة التسليح على العتبة الناتئة المدعمة بصفيحة من الحديد الخارجية

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الخلاصة:

الدراسة الحالية عبارة عن مقارنة عملية بين تأثير زيادة مقاومة الانضغاط للمقطع وزيادة نسبة التسليح على نتائج تقوية العتبات الخرسانية المسلحة باستخدام صفائح فولاذية ثابتة الأبعاد. يتكون البرنامج العملي من فحص عشر عتبات خرسانية. خمس

من هذه العتبات غير مزودة بصفائح فولاذية لغرض اتخاذها كنماذج أولية بينما تزود الخمس عتبات الأخرى بصفائح فولاذية بالأبعاد ذاتها تلصق إلى الأوجه السفلى لهذه العتبات.

ثلاث قيم من مقاومة الانضغاط تم استخدامها في هذه الدراسة وهي (22، 45 و 71 نت/ملم٢) وكذلك ثلاث نسب من التسليح الداخلي وهي (0.01411، 0.02116 و 0.03445) لغرض تقصي تأثيراتها على سلوك العتبات المقواة.

كشفت النتائج أن حمل التشقق والحمل الأقصى يمكن زيادتهما حتى (150% و 137%) على التوالي. وكذلك فإن بزيادة مقاومة الانضغاط للمقطع فإن كافة خصائص العتبة المقواة يمكن تحسينها بينما بزيادة نسبة التسليح فإن خاصتي الانحراف واالتشقق يمكن تقليلهما مما يحسن السلوك المرن للعتبة.

Introduction:

An important part of the responsibility of the structural engineer is to select, from many alternatives, the best structural system for the given conditions. The wise choice of a structural system is far more important, in its effect on overall economy and serviceability than refinement in proportioning the individual members **(**Nilson et al. 2003**)**. In structural engineering, the maintenance, repair and upgrading of structures are just as important and technical as the design and construction of new structures. In the case of upgrading this usually involves strengthening of an existing structure to satisfy a higher ultimate load and /or more stringent serviceability requirements **(**Jones et al 1982**)**. One of the more successful methods for strengthening the reinforced concrete structures is "Plate Bonding Technique". Investigations into the performance of members strengthened by this technique started in the 1960s. More recently, many researches on plain and reinforced concrete have been carried out.

The works of Jones et al. (1980), Swamy et al. (1987), Hamoush and Ahmed (1990), Oehlers et al. (1998) and Kheder et al. (2008) have highlighted a number of features of this technique, some of which can be summarized as:

- Full composite action can be achieved between a concrete member and a steel plate by the use of suitable epoxy glue.
- Plating has a considerable reducing effect on both flexural crack width and deflection. The reduction is greater than would be achieved by using additional internal reinforcement equivalent to that of external plate.
- Where failure of a strengthened reinforced concrete member is by yielding of bonded plate, the ultimate strength can be predicted by using conventional reinforced concrete theory accurately.
- This technique can increase the flexural stiffness of the beam at all load stages and consequently reduce deflections at corresponding loads with a significant increase in serviceability.
- Due to controlling of deflections, cracking and concrete strains, this technique increases the range of the elastic behavior of the strengthened beams.

However, despite of the plate bonding technique advantages in field of the reinforced concrete structures, the premature failure trouble is still dominant, as shown in **Figure 1**, and must be vanished to attain the technique advantages. Reinforced concrete beams strengthened externally by plates bonded to the tension face have been noted to fail in a variety of modes, influenced greatly by the plate thickness. Failure modes include the following **(**Nguygen et al 2001**)**:

- The flexural dominant mode; characterized by extensive yielding of internal reinforcement and external plate, deep intrusion of flexural cracks and crushing of concrete in the compressive zone.
- Premature separations of the plate at the concrete–glue–steel interface; initiated from the zone of plate curtailment.
- Horizontal tearing of concrete cover; initiated at the location of plate curtailment, the interface remains intact, with the crack passing through the concrete below the level of main internal reinforcement and proceeds upwards to the point of loading in a steep vertical ascent (shear mode of failure).

A hybrid mode of failure in which there is yielding of internal reinforcement and external plate prior to failure; with actual failure being precipitated by the horizontal tearing of concrete cover below the level of internal reinforcement (flexure, shear mode of failure).

Aims Of Study:

The aims of this study is to select from two options which one is the best for strengthening reinforced concrete beams using the plate bonding technique. The two investigated options are the effects of increasing the compressive strength of the section and increasing the reinforcement ratio on the strengthened beam behavior, whilst strengthening is done by external steel plate having same dimensions.

Experimental Work:

The experimental work consists of testing two groups of beams, the first group contains the original specimens (B1, B2, B3, B4 and B5) while the second group contains their strengthened specimens (SB1, SB2, SB3, SB4 and SB5) respectively. The beams (B1, B2 and B3) and their strengthened specimens have the same reinforcement ratio (ρ = 0.01411) but their compressive strengths are incremented (f'c = 22, 45 and 71MPa) respectively to investigate the compressive strength of section effect on the strengthened beams behavior. The beams (B3, B4 and B5) and their strengthened specimens have the same compressive strength (f'c = 71MPa) but their internal reinforcement ratios are incremented (ρ = 0.01411, 0.02116 and 0.03445) respectively to investigate the reinforcement ratio of section effect on the strengthened beams behavior.

Ten beams are tested under two point loading up to failure to study their strength and deformation characteristics in addition to the mode of failure and ductility. Five of the tested beams are without external steel plates to be the original specimens while the other five ones are provided with external steel plates of same dimensions glued at the bottom face of the beams.

Materials

Concrete

Three concrete mixes were used to provide three compressive strengths of (22, 45 and 71 MPa), as shown in Table 1. Ordinary portland cement Type (I) complying with the Iraqi standard specification No. 5/1984. The used fine aggregate was natural river sand with fineness modulus (F.M.) of (2.73), bulk specific gravity (S.G.) of (2.64) and sulfate content, (SO3%) of (0.31%) by sand weight, which is less than the limit of Iraqi standard specification No. 45/1984. The used coarse aggregate is crushed gravel with maximum size of (12mm); the bulk specific gravity (S.G.) of this aggregate is (2.61) and complying with the Iraqi standard specification No. 45/1984. For increasing the compressive strength, a superplasticizer (SP) was used to reduce the water content and compensate the associated reduction in workability, is commercially known as (Glenium 51) which complies with ASTM C 469–86.

Cylinders and prisms for control tests were cast and stored with each beam and then tested when the beam was tested. The mix proportions and the average results of cylinder strength f'c, modulus of rupture fr and Elastic modulus Ec for all beams are given in Table 1:

Reinforcement

Two types of reinforcing steel are used in present work, as shown in Table 2; steel bars used as internal reinforcement for flexure and shear in all beams and steel plates used as external reinforcement as well as other internal steel bars in the strengthened beams. Deformed steel bars of diameter (16, 25mm) are used for the main reinforcement and plain steel bars of diameter (6mm) are used for stirrups. A steel plate with (1.0mm) thickness is used as external reinforcement in the strengthened beams by bonding to the concrete surfaces by epoxy resin of mechanical properties and especially bond strength greater than the concrete tensile strength.

Details of Beams

All the beams were with dimensions of (150x250x2500mm), and their spacing of stirrups and the limitations of reinforcement were adopted according to ACI Code 318–05, as shown in **Table 3** and **Figure 2**. The shear span (a/d) for all the beams was constant at (4.21) and provided with steel bar stirrups of (2 legs Ø6mm at 100mm). For the strengthened specimens (SB1, SB2, SB3, SB4 and

SB5), external steel plates with dimensions of (100x1x2500mm) were glued at the bottom faces of the beams.

Casting and Curing of Beams

Two steel molds were prepared for casting the specimens; so that two beams were cast at the same time at one day. Six cylinders and three prisms were cast with each two beams for observing the concrete mechanical properties. The concrete was poured at (3 layers) and compacted about (2 min) by a vibrating table. After (2 days), the two specimens and their control units were removed from their molds and cured in water containers at a temperature of about (25°C) until the testing age of (28 days).

For the strengthened specimens, the external steel plates were glued at the specimens surfaces by the epoxy resin (glue), as shown in **Figure 2.**

Preparation and Testing of Beams

Before testing, the specimens were painted with a white emulsion to aid the detection of cracks. Dial gauge with 0.01mm divisions was positioned at the bottom of beam center.

All beams were tested under two–point loading, each equal to (1/2) the total applied load from the loading machine. Loading was applied in increments of (4kN) to record the deflection. After each (20kN), the load is kept constant until the required readings of crack widths. Testing was continued until the beam showed a drop in load carrying capacity with increasing deflection.

Testing was conducted by using MFL SYSTEM of hydraulic universal testing machine type EPP300, as shown in Figure with a maximum capacity of (3000kN).

Experimental Results:

The experimental test insisted on cracking load, failure load, deflection, cracks and their characteristics as well as mode of failure. Table 4 contains the exhibited values of the above properties.

Cracking Load

It is obvious from Table 4 that for the original beams (B1, B2 and B3) which represent the compressive strength increment the appearance of first crack was at load having ratio (16, 19 and 31%) of their failure loads, while for the beams (B4 and B5) which represent the reinforcement ratio increment the appearance of first crack was at load having ratio (20 and 15%) of their failure loads respectively. On the other hand, when strengthen all these beams by constant dimensions plates the cracking load raised about (8kN) but the ratio of the cracking load at the strengthened beam to original one was decreased in the both cases; with increasing the compressive strength or increasing the reinforcement ratio but with by increasing the reinforcement ratio the decrease was largest as shown in Table 5. From the previous demonstration of results it is clear that increasing the compressive strength is better than increase the reinforcement ratio for increasing the ratio of cracking load to failure load and to delay the appearance of the first crack in comparison the beam ultimate strength.

Failure Load

The failure load can be raised by increasing the compressive strength or increasing the reinforcement ratio, but from **Table 4** the results showed that for the beams (B1, B2 and B3) the failure loads were (101, 104 and 106kN) respectively and this mains slight increase in the ultimate strength in comparison with the increase in the compressive strength. While, by comparison between the beams (B3, B4 and B5) which represent the increase in the reinforcement ratio, their failure loads were (106, 176 and 253kN) and reflected the considerable in the ultimate strength. Thus, it is concluded that the reinforcement ratio has the greatest effect on improving the ultimate strength of the beam more than the compressive strength. For the strengthened specimens (SB1, SB2 and SB3) the ratio of the strengthened failure load was (1.18, 1.26 and 1.37) respectively and referred to the activity of increasing the compressive strength in improving the failure load through the strengthening by plate bonding technique. In contrast with the compressive strength action; the reinforcement ratio when increased led to reduce the ratio of strengthened failure load as (1.37, 1.28 and 1.17) respectively observed for (SB3, SB4 and SB5) respectively. So that, it is concluded that the compressive strength has the greatest effect on improving the ultimate strength of the strengthened beam more than the reinforcement ratio.

Deflection

From **Table 4** where the values of deflection were listed; it is noticed that the deflection proportions to the failure load of the beam, therefore, the deflections of (B1, B2 and B3) were smaller than the deflections of (B4 and B5). The strengthening process exhibited a considerable reduction in deflection especially for (SB4 and SB5) in according with the ratio of strengthened failure load to original failure load when this ratio decreases with the increase in the reinforcement ratio as shown in **Table 5**. On the other side, the load-deflection curves in **Figure 4** clarify the similarity in the strengthened beams behavior to that of the original ones.

Ductility

Typically, ductility is calculated by division the value of deflection at failure per the value of deflection at yield condition and this defined as deflection ductility. That is known by decreasing the compressive strength, increasing the reinforcement ratio or increasing the yield strength of the reinforcement the ductility will decrease and the reported effect of flexural strengthening with external reinforcement is a reduction in the ductility relative to the original condition (ACI Committee 440 2002). The results of the present study confirms the previous report because all the strengthened beams exhibited ductility less than that of original specimens and this came from the increase in reinforcement due to the external steel plate, and for the same reason the ductility of (B4 and B5) was (0.65 and 0.67) which is less than (0.78, 0.76 and 0.77) belong to (B1, B2 and B3) respectively

Cracking

Cracking was observed by three variables in the present study; crack width (W_u), crack height (h) and crack spacing (s) as shown in **Table 4.** The crack spacing is a function of the number of cracks along the beam. It is noticed that number of cracks was the same in all the strengthened beams and almost less by one crack than that of their original beams and that conforms too many previous researches that stated that plate bond technique has a marginal effect on crack spacing. For the crack width; the original beams (B1, B2 and B3) exhibited reduction in the crack width from (1.45mm) to (1.35 and 1.25mm) respectively to reflect the effect of increasing the compressive strength on reduction the crack width, and after this the beams (B4 and B5) exhibited a constant crack width of (1.25mm) with no effect of increasing their reinforcement ratio. All the strengthened beams exhibited a reduction in crack width and reflected the activity of the plate bonding technique in reduction the crack width. For the crack height; the original beams (B1, B2 and B3) exhibited a crack height of (177, 193 and 199mm) respectively to reflect the effect of increasing the compressive strength on raising the crack height, but for the beams (B3, B4 and B5) the crack heights were (199, 195 and 178mm) respectively to reflect the effect of increasing the reinforcement ratio on diminishing the crack height. The strengthened beams (SB1, SB2 and SB3) which have the same exhibited a same crack height about (173mm) and when reinforcement ratio in the beams (SB4 and SB5) the crack height was more diminishing to be less than (173mm) and to reflect a new prove on the activity of the plate bonding technique in restraining the cracking.

Mode of Failure

The urgent problem of the plate bonding technique is the concentration of stresses at the plate ends which lead to premature failure and limit the advantages of this technique. Extension the external steel plate reduces the concentration stresses at the plate ends so that the steel plates were bonded along the strengthened beams to ensure a desirable failure. Thereby, all the beams failed by the same manner as mentioned in **Table 4** which was flexure mode characterized by developing of cracks coinciding with rapid increase in deflection continued until the drop of the applied load and indicated yielding of reinforcement left residual deformations after releasing of the load as shown in **Figure 5.**

Conclusions:

1. Increasing the compressive strength is more preferable than increasing the reinforcement ratio for increasing the cracking load of the strengthened beam with external steel plate and with normal concrete strength best controlling on the cracking load can be achieved.
2. The reinforcement ratio has the efficiency for increasing the ultimate strength of the beam more than the compressive strength, but after strengthening; increasing the compressive strength is more preferable than increasing the reinforcement ratio for enhancing the ultimate strength.
3. The plate bonding technique has a control rule in reduction the deflection of the beam, and this reduction can be raised by increasing the reinforcement ratio.
4. There is loss in ductility of the strengthened beam due to the further use of reinforcement and this loss increases with increase the reinforcement ratio. However, the ductility can be restored by increasing the compressive strength of the beams.
5. The plate bonding technique has a restraint effect for reduction the crack width, the crack width and cracks number.
6. In spite of the action of external steel plate on increasing the reinforcement ratio and then decreasing the ductility, but this action enhances the activity of the internal reinforcement for restraining the cracking and reduction the deflection and leads to increase the elastic behavior range of the beam.

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Table 1: Mix proportions and mechanical properties of concrete

Mix	Mix Proportions kg/m^3					Mechanical Properties MPa				
	Cement	Sand	Gravel	Water	SP	f'_c	f_r	† f_r	E_c	‡ E_c
1	345	700	1125	220	–	22.0	3.6	3.3	24200	22195
2	415	581	1096	185	4.1	45.0	6.2	4.7	32954	31528
3	560	635	1085	150	8.4	71.7	8.1	5.9	40500	39798

† $f_r = 0.7(f'_c)^{(0.5)}$

‡ $E_c = 4700\ (f'_c)^{(0.5)}$

Table 2: Properties of reinforcement

Reinforcement	Bar Diameter (Ø) mm	Plate Thickness (t) mm	Modulus of Elasticity (E_s) GPa	Yield Stress (f_y) MPa	Ultimate Stress (f_u) MPa
Steel Bar	6 plain	-	200 †	383	545
	16 deformed	-	200 †	518	635
	25 deformed	-	200 †	448	709
Steel Plate	-	1.0	200 †	280	347

†Assumed (E_s).

Table 3: Details of beams

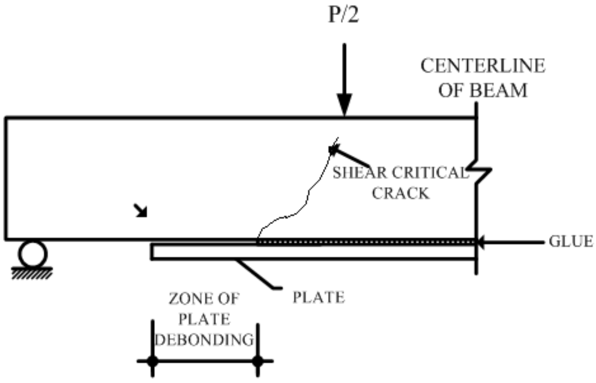
Beam	Compressive Strength (f'_c) MPa	Internal Steel Bars mm^2	External Steel Plate mm^2	Reinforcing Ratio (ρ) %	Upper Limit (ρ_{max}) %	Lower Limit (ρ_{min}) %
B1	22	402.12	-	1.411	1.647	0.270
SB1	22	402.12	100	1.555	1.647	0.270
B2	45	402.12	-	1.411	2.943	0.324
SB2	45	402.12	100	1.555	2.943	0.324
B3	71	402.12	-	1.411	4.064	0.407
SB3	71	402.12	100	1.555	4.064	0.407
B4	71	603.18	-	2.116	4.064	0.407
SB4	71	603.18	100	2.260	4.064	0.407
B5	71	981.75	-	3.445	5.013	0.470
SB5	71	981.75	100	3.611	5.013	0.470

Table 4: Results of test

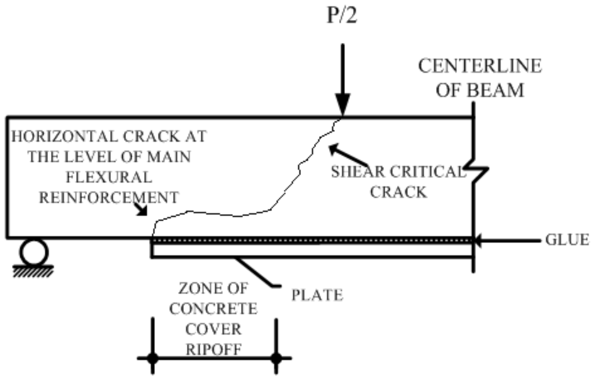
Beam	Cracking Load (P_{cr}) kN	Failure Load (P_u) kN	Deflection at Yield (Δ_y) mm	Deflection at Failure (Δ_u) mm	Deflection Ductility (Δ_u/ Δ_y) mm	Crack Width (W_u) mm	Crack Height (h) mm	Crack Spacing (s) mm	Mode of Failure
B1	16	101	11.40	18.86	1.65	1.45	177	83	flexure
SB1	24	119	14.67	18.87	1.29	1.20	173	83	flexure
B2	20	104	12.14	21.34	1.76	1.35	193	80	flexure
SB2	28	131	15.35	20.43	1.33	1.20	173	83	flexure
B3	33	106	13.21	24.27	1.84	1.25	199	77	flexure
SB3	42	145	17.13	24.10	1.41	1.15	173	83	flexure
B4	36	176	18.07	40.22	2.23	1.25	195	78	flexure
SB4	44	226	17.28	25.36	1.46	1.15	171	83	flexure
B5	38	253	18.85	41.66	2.21	1.25	178	81	flexure
SB5	46	295	17.53	26.01	1.48	1.15	160	83	flexure

Table 5: Ratios of strengthened to original beams properties

Beams	Cracking Load (P_{cr})	Failure Load (P_u)	Deflection at Failure (Δ_u)	Deflection Ductility (Δ_u/ Δ_y)
SB1/B1	1.50	1.18	1.00	0.78
SB2/B2	1.40	1.26	0.96	0.76
SB3/B3	1.27	1.37	0.99	0.77
SB4/B4	1.22	1.28	0.63	0.65
SB5/B5	1.21	1.17	0.62	0.67

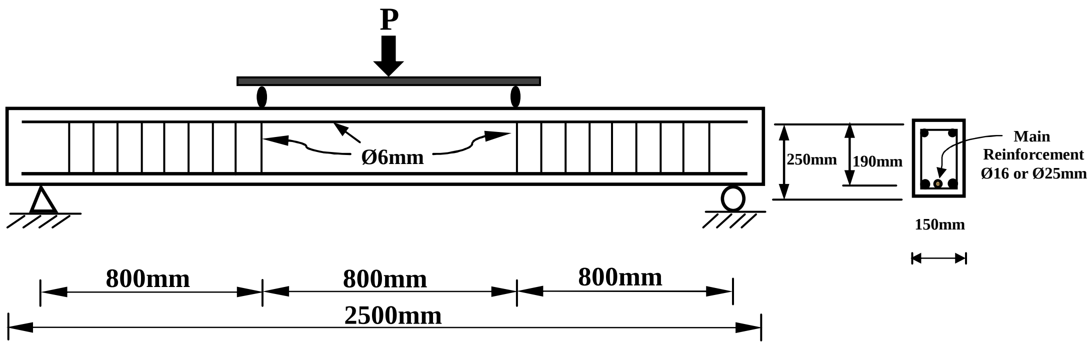


a) *Plate debonding*

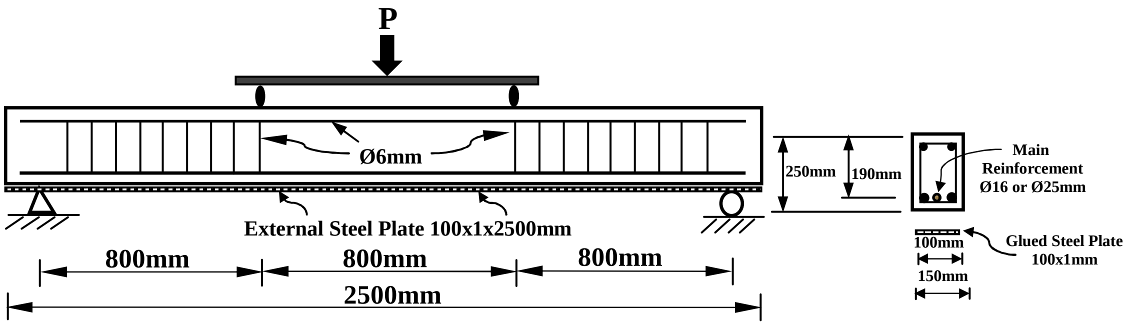


b) *Ripping off concrete cover*

Figure 1: Premature failure hazards (Sharif 1994)



a) *Original beams*



b) *Strengthened beams*

Figure 2: Details of beams

Figure 3: Testing machine

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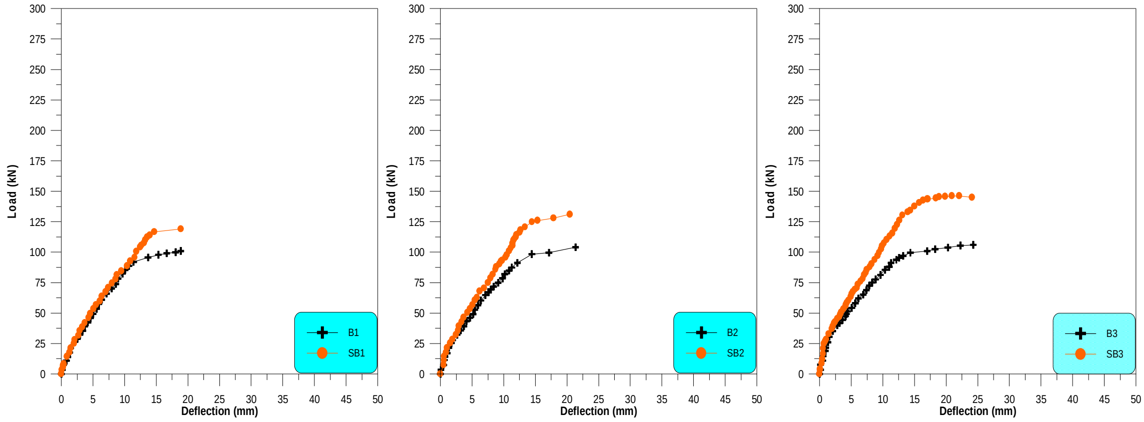
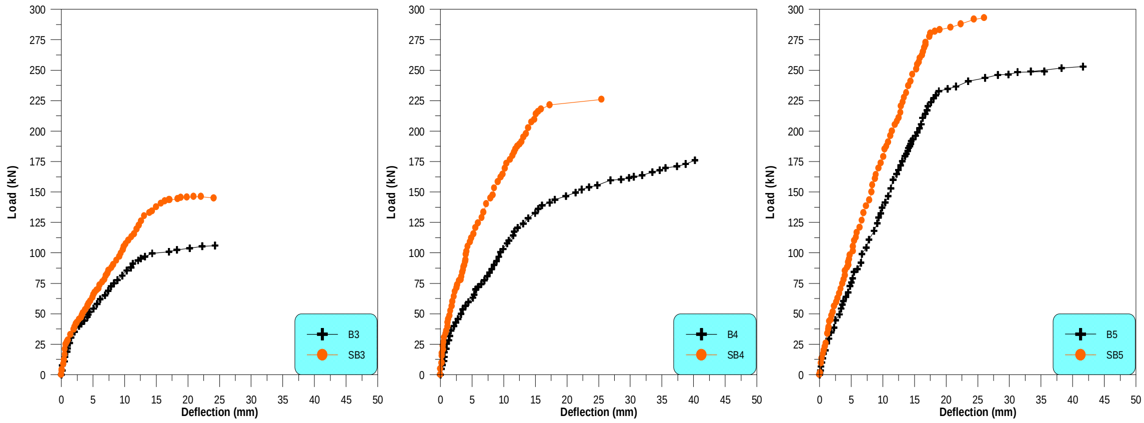


a) *Specimens with incremented compressive strength*



b) *Specimens with incremented reinforcement ratio*

Figure 4: Load-Deflection curve of the testes beams

Figure 5: Deformation of beam after testing