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Behavior of Reinforced Concrete Beams Strengthened With Carbon Fiber Strips

سلوك الكمرات الخرسانية المسلحة المقواة بشرائح الكربون

by

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مستخلص:

في هذا البحث تم لصق شرائح خارجية من ألياف الكربون لتقوية الكمرات الخرسانية المسلحة وقد تم دراسة تأثير إضافة هذا الشرائح على عدد ست عشرة كمرة خرسانية مسلحة قطاعها العرضي ١٢×٢٠ سم وطولها ٢٣٠ سم. ومن النتائج التي تم الحصول عليها زيادة السعة التحميلية فى الإنحناء للكمرات التي تم تقويتها بشرائح الكربون بنسب تتراوح بين ١٢% حتى ٤٠% مقارنة بالكمرة المرجعية غير المقواة. كما تم زيادة السعة التحميلية فى القص للكمرات التي تم تقويتها بشرائح من ألياف الكربون بنسب تتراوح بين ١٠,٥% حتى ٥٢,٦% مقارنة بالكمرة المرجعية. ومن نتائج البحث أيضا زيادة جساءة الكمرات المقواة بشرائح الكربون المسلح وانخفاض قيم الترخيم وانتظام توزيع الشروخ فيها.

Abstract:

This paper aims to evaluate the improvement of load carrying capacity of reinforced concrete beams strengthened by Carbon Fiber Reinforced Polymer (CFRP) strips. Sixteen reinforced concrete beams with a cross section of 120x200 mm and a total length of 2300 mm, were fabricated, strengthened, and loaded up to failure. The results showed that the externally bonded CFRP strips increase the flexural and shear capacities of reinforced concrete beams. For example, the flexural capacity of strengthened beams increased by 12-40%, while the shear capacity increased by 10.5-52.6%. The stiffness enhancement varied from 10 to 79% depending on the applied strengthening mode. A reduction in deflection for all strengthened beams was observed and recorded.

1. Introduction

The term strengthening means upgrading the strength of a structure to make it capable of resisting larger loads. Strengthening becomes necessary when there is an increase in load requirements, change in use, or deterioration due to aggressive environment and harsh atmosphere. It is also necessary to resist impact and earthquake shocks. Many simple techniques have been developed to strengthen almost all kind of structures [1-4]. However, one of the most remarkable techniques presented is the use of non-metallic lightweight materials such as fiber reinforced polymers (FRP) which appear as a competitive alternative material [5-8]. Extensive research on the use of FRP in concrete structures started in Europe, USA and Japan about 25 years ago. FRP plates or fabrics provide high strength, light weight, resistant to chemicals, good fatigue strength, non-corrosion, and the ability to form complex shapes.

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FRP materials are generally elastic up to failure and exhibit neither a yield point nor a region of plasticity. They tend to have low strain to failure (less than 3%). The resulting area under the stress/strain curve, which represents the work done to failure, is relatively small when compared to many metals [9]. FRP generally constructed of high performance fibers such as carbon, aramid or glass which are placed in a resin matrix like epoxy or polystyrene. By selecting among the many available fibers, geometric and polymers, the mechanical properties can be tailored for a particular application. The carbon fiber reinforced polymer (CFRP) is a new and highly promising material in structural application because of its extraordinary mechanical properties allowing significant increases in strength and stiffness. Recent developments have included carbon fibers with tensile strength approaching up to 800 GPa. Carbon fibers typically have a diameter varies from 5 to 8 microns, which is much smaller than human hair [10]. Unidirectional CFRP exhibits linear stress-strain behavior up to failure load. CFRP strain is much higher than typical yield strains of steel. From the mid-1980s through the early 1990s, Japanese, American and Swiss investigators conducted research on the use of CFRP wrapping systems for strengthening concrete bridge columns to resist collapse during seismic events. Although the material is relatively expensive, the case of installation allows significant savings in labor and equipment cost compared with conventional strengthening methods. A cost comparison of bridge strengthening with steel plates and CFRP plates showed that CFRP strengthening offered a 17.5 percent cost reduction [11, 12].

2. Objectives

The work presented in this paper experimentally investigates the behavior of the reinforced concrete beams strengthened with externally bonded carbon fiber reinforced polymer (CFRP) fabrics. The main objectives of this research are:

1. To investigate the behavior of reinforced concrete beams strengthened with externally bonded carbon fiber reinforced polymer (CFRP) fabrics.
2. To clarify the failure modes of strengthened reinforced concrete beams subjected to shear and flexure.
3. To study the relationship between cross section area of CFRP and reinforcement steel area.

3. Experimental Investigation

3.1 Scheme and Program

Sixteen reinforced concrete beams with cross section of 120×200 mm depth and total length of 2300 mm were cast and tested. The beams were divided into four groups, each group contains four beams.

Two groups were strengthened against flexural failure and were called BF1 & BF2 respectively while other groups were strengthened against shear failure and were called BS1 & BS2 respectively. The main parameter of this study is focused on investigating the effect of strengthening ratio and mode. The variables include; longitudinal reinforcement ratio ($\mu=A_s/A_c$), shear span to depth ratio (a/d), strengthening ratio ($\rho=A_f/A_s$) and strengthening mode. Table (1) illustrates these variables.

3.2 Materials

The type of cement used was ordinary Portland cement (ASTM Type I), with specific weight of 3.11 and fineness of 2800 cm^2/gm. Siliceous aggregates with specific weight of about 2.63 were used. The maximum nominal aggregates size was about 20 mm. The fineness modulus of fine aggregates was 3.12. High grade steel with yield strength of 400 MPa was used for longitudinal reinforcement while mild steel (f_y=245 MPa) was used for stirrups. Carbon fiber reinforced polymer (CFRP) was unidirectional fabric type. This fabric was 305 mm wide, 0.13 mm thickness, and 225 gm/m^2 density. According to manufacturer's catalogue, CFRP has 3500 MPa tensile strength, and 230 GPa tensile elastic modulus. The elongation of CFRP at break was about 1.5%. Epoxy resin with two components was used as adhesive material. It allows bonding structural parts and elements, also assures evenly distributed stress transmission over the whole concrete surface area. The density of mixed epoxy was 1.3 kg/liter and the pot life was 30 minutes at 35 C^0. Internal and external electrical strain gauges (Type KC-70-120 A1-11) were used in flexural specimens while internal strain gauges only were used in shear specimens. The gauge length was 67 mm.

3.3 Concrete Mix

The concrete was mixed in a concrete drum mixer with a capacity of 100 liters. One cubic meter of concrete consists of 350 kg of cement, 640 kg of fine aggregates, 1280 kg of coarse aggregates and 165 liters of fresh water. The constituents were mixed in dry state for about two minutes. Mixing water was added gradually during mixing for about three extra minutes. The consistency of fresh concrete was measured by conventional slump test. The concrete was cast in steel shutters and compacted by vibrating table to insure full compaction. Steel shutters were chosen to achieve regular dimensions, right angle corners and fair face surfaces. Six cubes 150×150×150 mm and two plain concrete beams 100×100×700 mm were cast and tested to determine the compressive strength and the modulus of rupture of concrete for each beam specimen. After 24 hours, all specimens and the sides of steel shutters were demolded and all specimens were covered with wet canvas for seven days to insure full curing. The average compressive strength was 34 MPa, while the modulus of rupture lies in the vicinity of 3.96 MPa.

4. Strengthening Modes

4.1 Flexural Groups

Flexural groups consist of two groups as BF1 and BF2. Group BF1 consists of four beams with 2ϕ12 lower reinforcement, 2ϕ10 upper reinforcement, and 10ϕ6 /m` stirrups. Group BF2 consists of four beams with 2ϕ16 lower reinforcement, 2ϕ10 upper reinforcement, and 10ϕ6 /m` stirrups. Fig. (1) showed the strengthening modes for these beams which may be distinguished as:

- BF1-1 was defined as control beam or reference beam without any strengthening system.
- BF1-2 was strengthened by external single-flat layer of CFRP fabrics with cross section of 120×0.13 mm and 1500 mm total length. The CFRP sheet was applied on the bottom of the beam (tension face). U-shape anchorages were fixed at the ends of the sheet to prevent debonding of the longitudinal CFRP. End anchorage consist of two layers of CFRP sheet with cross section of 60×0.13 mm each layer with full height of the beam.
- BF1-3 was externally strengthened same as BF1-2 but the longitudinal CFRP sheet was double layers instead of single layer.
- BF1-4 was externally strengthened by single layer of longitudinal CFRP fabrics with cross section of 240×0.13 mm. The breadth of CFRP was selected to completely cover the beam bottom (tension face) in addition to 60 mm upward on each side of the beam. End anchorages were same as in BF1-2.
- BF2-1 was defined as control beam or reference beam without any strengthening system.
- BF2-2 was strengthened by external double-flat layers of CFRP fabrics with cross section of 110×0.13 mm and 1500 mm total length. The CFRP sheet was applied on the bottom of the beam (tension face). U-shape anchorages were fixed at the ends of the sheet to prevent debonding of the longitudinal CFRP. End anchorage consists of two layers of CFRP sheet with cross section of 60×0.13 mm each layer with full height of the beam.
- BF2-3 was externally strengthened by single layer of longitudinal CFRP fabrics with cross section of 220×0.13 mm. The breadth of CFRP was selected to completely cover the beam bottom (tension face) in addition to 50 mm upward on each side of the beam. End anchorages were same as in BF1-2.

- BF2-4 was externally strengthened same as BF2-3 but the longitudinal CFRP sheet was double layers instead of single layer.

4.2 Shear Groups

Shear groups consist of two groups, each group contains four beams. The first group was defined as BS1, while the other one was defined as BS2. The Beams in group BS1 was reinforced with 2ϕ16 lower reinforcement, 2ϕ12 upper reinforcement, and 5ϕ6 /m` stirrups. Whereas, Beams in group BS2 was reinforced with 2ϕ18 lower reinforcement, 2ϕ12 upper reinforcement, and 5ϕ6 /m` stirrups. Strengthening modes of beams in shear groups are shown in Fig. (2) and can be defined as:

- BS1-1 was defined as control or reference beam without external strengthening.
- BS1-2 was strengthened against shear failure. The strengthening mode consists of three strips U-shape single layer covering the full depth of the beam. The strip cross section of 60×0.13 mm was applied perpendicular to longitudinal axis of the beam. The spacing from centerlines of the strips to the support was 205, 365, and 525 mm respectively.
- BS1-3 was strengthened same as BS1-2 but each strip was double layers instead of single layer.
- BS1-4 was strengthened by three vertical side strips double layers with full depth of the beam. Cross section of strips and spacing same as BS1-3.
- BS2-1 was defined as control beam or reference beam without any external strengthening.
- BS2-2 was strengthened against shear failure by three side strips with full depth of the beam. The strip cross section of 60×0.13 mm was applied at 45° to longitudinal axis of the beam. The spacing from centerlines of the strips to the support was 340, 500, and 660 mm respectively.
- BS2-3 was strengthened such as BS2-2 but strips were double layers.
- BS2-4 was strengthened by side strip double layers with full depth of the beam. The strip cross section of 200×0.13 mm was applied perpendicular to longitudinal axis of the beam at clear distance 300 mm from each support.

5. Strengthening Procedures

The external strengthening system (CFRP sheets and epoxy adhesives) was performed as follows:

1. Preparation of concrete surface by grinding disk. Loose particles and dust have been removed by vacuum cleaner. The concrete surface has been dried by hot air blower.
2. The surface was leveled and structural corners had been rounded to a radius of 10 mm by diamond grinding disk.
3. Epoxy resin was mixed separately, then, component **B** was added to component **A** using special spatula.

4. Stir with an electric mixer for about 3 minutes until all the colors streaks disappeared, then the whole mix was poured into clean container and stir again for about extra one minute at a low speed to keep air entertainment at a minimum.
5. The mixed resin was applied to the prepared concrete surface by brush in a rate of 1.2 kg/m^2 according to manufacturer's recommendations.
6. Carbon fiber fabrics was placed onto the epoxy coating and squeezed with plastic roller.
7. The second layer of fabrics was applied within twenty minutes using epoxy resin with average dosage of 0.6 kg/m^2 according to manufacturer's recommendations.

6. Test Procedure

All specimens were tested as simple beams with clear span of 2000 mm using a four-point loading system. The concentrated load was applied on steel distribution beam used to generate the two concentrated load on each specimen. The load was applied by means of a hydraulic reversed pump. This load was monotonically increased from zero up to failure load. The beams in flexural groups (BF1, and BF2) were tested with shear span to effective depth ratio (a/d) = 4.55, while beams in shear group (BS1, and BS2) were tested with (a/d) = 3.33 and 2.42 respectively. In flexural groups, each specimen was supplied with internal electrical-strain gauge before casting. The strain gauge was fixed at the midpoint of the longitudinal bottom bar, while external strain gauge was fixed on CFRP at its midspan. In shear groups, each specimen was supplied with internal eclectic strain gauge only. It was fixed at the bottom of one stirrup faraway 25 cm from support. Both internal and external electric strain gauges were connected to digital strain instrument. The strain was measured in longitudinal reinforcement and CFRP at different loading stages. Deflection was also recorded at different loading stages by the use of three mechanical dial gauges which were applied at midspan and under each loading point as shown in Fig. (3)

7. Test Results

7.1 Flexural Strengthening

The failure load and failure mechanism of beams with flexural strengthening are summarized in Table (2). The enhancement ratios of the ultimate load for each beam are also shown in Table (2). For beams with light reinforcement ratio (μ=1.1%), the enhancement of the load carrying capacity varied from 20 to 40 % depending on the strengthening mode and ratio. The corresponding enhancement in the beams with heavy reinforcement ratio (μ=1.97%), ranged from 12 to 31.6% depending also on the strengthening ratio and mode. This means that, the enhancement percentage of light reinforced beams is higher than that of heavy reinforced beams. On the other hand, strengthening ratio has a significant effect in improving the loading capacity. For example, the load carrying capacity increased from 20 to 36% when the strengthening ratio was doubled (BF1-2 and BF1-3). At the same time, when double U-shape strengthening was used, the loading capacity of BF2-4 increased with 31.6% compared to 16% for beam BF2-3 strengthened with single U-shape mode. At a given strengthening ratio, the beam strengthened with single U-shape layer (BF1-4) exhibited loading enhancement of about 40% compared to 36% for beam with double–flat bottom layers (BF1-3). Meanwhile, the results of beam BF2-2, and BF2-3 indicated that, the use of single U-shape layer is more efficient than the use of double-flat layers. On the other hand, the loading capacity increased with about 16 and 31.6% when single and double U-shape were used respectively. However, selection of U-shape modes (single layer or double layers) prevented the flexural cracks allover the span during the stages of loading as observed during the test of beams BF1-4, BF2-3 and BF2-4. Failure shapes of these beams are shown in Fig. (4).

The immediate deflection of a beam depends mainly on the case of loading, span, restraints, section geometry and material properties. The applied load versus midspan immediate deflection for beams subjected to flexure were nearly similar for all beams at the early stages of loading. The strengthened beams showed less deflection than that of the control beams as shown in Figs. (5), and (6). The deflection under the loadings point was recorded elsewhere [13].The stiffness is defined as the load capacity of a section at a given deflection. In this study, the deflection was chosen to be 1/400 of the clear span, i.e. 5 mm [14]. This deflection approximately occurred at about 60% from the failure load of the control beams. The stiffness enhancement of flexural beams can be shown in Fig. (7).

In beams with light reinforcement ratio (μ=1.1%), the enhancement of beam stiffness was significantly higher than that of beams with heavy reinforcement (μ=1.97%). On average, stiffness enhancement of beams BF1-2, BF1-3, and BF1-4 was about 46.8 %, while in beams BF2-2, BF2-3, and BF2-4 the average enhancement was about 18.2%. For beams without strengthening, stiffness changed from 27 to 44 kN when the longitudinal reinforcement ratio changed from 1.1 to 1.97% respectively. It is worth noting that, at a given strengthening ratio, stiffness increased significantly when the shape of strengthening changed from flat layer (BF1-3) to U-shape layer (BF1-4). However, insignificant increase of stiffness (from 16 to 18%) was observed when strengthening shape changed from flat layer (BF2-2) to U-shape layer (BF2-3) in beams with higher longitudinal reinforcement.

7.2 Shear Strengthening

The failure load and failure mechanism of beams in shear group are summarized in Table (3). The enhancement of load capacity of each beam can also be shown in the same table. The enhancement of the load carrying capacity depends mainly upon the shear span to depth ratio (a/d) and strengthening modes and ratios. For the beams with a/d=3.33 the enhancement ratio varied from 13.3 to 24.40%, while for the beams with a/d=2.42 the enhancement ratio varied from 10.5 to 52.6%. This identically clarified that, the smaller a/d is the higher enhancement ratio. Strengthening mode and number of layers have a significant effect in improving the load capacity. For example, using U-shape single layer and double layers improved the load capacity up to 13.3% and 24.4% respectively as comparison between BS1-2, BS1-3. This means that, the enhancement ratio was approximately doubled when U-shape single layer changed to U-shape double layers. Also the effect of double layers had significant effect as comparisons between BS2-2, BS2-3. For a given strengthening modes (number and cross section of layers), the load capacity was affected by the spacing of the layers. For example BS2-3 and BS2-4 had the same layers and cross section but the spacing was different. This spacing had significant effect on the load capacity enhancement (52.6 and 10.5% respectively) i.e., the spacing of layers had significant effect on the enhancement ratio as mentioned above. The shapes of failure of some beams in shear group are shown in Fig. (8).

The immediate midspan-deflection of beams in shear group was recorded as shown in Figs.(9), (10). The strengthening ratio and stiffness enhancement of shear beams are shown in Table (4). The stiffness enhancement varied from 7.3 up to 27.3% depending mainly on the number of layers and strengthening mode. The stiffness slightly increased in shear group compared to flexural group i.e., the enhancement percentage in flexural group varied from 13.6 up to 66.6%, while in shear group, the enhancement varied from 7.3 up to 27.3%. The stiffness enhancement depends mainly on the shear span to depth ratio (a/d) i.e., the smaller a/d is the higher stiffness ratio, where in the group BS1 (a/d = 3.33), the stiffness ratio varied from 7.3 up to 18.87% and in the group BS2 (a/d = 2.42) the stiffness ratio varied from 7.3 up to 27.3%.

8. Conclusions

The most notable conclusions from this study are given as follows:

1 Significant enhancement of flexural strength is obtained in lightly reinforced beams (μ=1.1%). For more heavily reinforced beams (μ=1.97%) flexural strength enhancement is less.

2. In the Strengthened beams with light reinforcement (μ=1.1%), the enhancement of the load carrying capacity varied from 16.5 to 40 % depending on the strengthening ratio and mode. In the beams with heavy reinforcement ratio (μ=1.97%), the enhancement ratio ranged from 12 to 31.6%. This means that the higher the reinforcement ratio, the less the enhancement of the load carrying capacity due to strengthening with CFRP.

3. Strengthening ratio has a significant effect in improving the loading capacity. For example, the load carrying capacity increased form 16.5 to 36 % when the strengthening ratio ($\rho=A_f/A_s$) changed from 7 to 14 % (BF1-2 and BF1-3).

4. At a given ρ, the strengthening U-shape double layers exhibited loading enhancement of about 40% compared to 36% for strengthening with flat double layers (BF1-4 and BF1-3).

5. The stiffness of the strengthened beams with light reinforcement ratio (μ=1.1%) was significantly higher than that of the beams with heavy reinforcement ratio (μ=1.97%). On average, the stiffness enhancement of beams BF1-2, BF1-3 and BF1-4 was about 42.6 %, while in beams BF2-2, BF2-3 and BF2-4 the average enhancement was about 21 %.

6. It is worth noting that, at a giving strengthening ratio, the stiffness increased significantly when the strengthening mode changed from flat layers (BF1-3) to U-shape layers (BF1-4).

7. The enhancement of shear strength depends mainly on the shear span to depth ratio (a/d), strengthening modes and ratios. For beams with a/d = 3.33, the enhancement ratio varied from 13.3 to 24.4%, while for the beams with a/d = 2.42, the enhancement varied from 10.5 to 52.6%. This means that, the smaller a/d is the higher enhancement ratio.

8. The mode of strengthening against shear failure and the number of layers has a significant effect in improving the load capacity. For example, U-shape mode single layer and double layers mode improved the load capacity from 13.3 to 24.4 % respectively (BS1-2 and BS1-3).

9. For a given strengthening mode (number of layers and cross section), the loading capacity was affected by the spacing of the layers. The spacing had significant effect varied from 10.5 to 52.6% as comparison between BS2-4 and BS2-3

10. The stiffness slightly increased in shear group compared to flexural group. The enhancement in flexural group varied from 16 to 60 % compared to 9 to 36.4% in shear group. This means that the mode of shear strengthening has slightly enhancement in stiffness.

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Table (1) Variables of Test Program.

Mode	Group No.	Beam No.	$\mu = \frac{A_s}{A_c}\%$	$\rho = \frac{A_f}{A_s}\%$	a/d	Strengthening modes
FLexural Strengthening	I	BF1-1	1.10	0.0	4.55	Reference (without strengthening)
		BF1-2	1.10	7.0	4.55	Single flat layer
		BF1-3	1.10	14.0	4.55	Double flat layers
		BF1-4	1.10	14.0	4.55	U-shape single layer
	II	BF2-1	1.97	0.0	4.55	Reference (without strengthening)
		BF2-2	1.97	7.0	4.55	Double flat layers
		BF2-3	1.97	7.0	4.55	U-shape single layer
		BF2-4	1.97	14.0	4.55	U-shape double layers
Shear Strengthening	III	BS1-1	1.97	-	3.33	Reference (without strengthening)
		BS1-2	1.97	-	3.33	Three vertical U shape strips single layer
		BS1-3	1.97	-	3.33	Three vertical U shape strips double layers
		BS1-4	1.97	-	3.33	Three vertical side strips double layers
	IV	BS2-1	2.12	-	2.42	Reference (without strengthening)
		BS2-2	2.12	-	2.42	Three inclined side strips single layer
		BS2-3	2.12	-	2.42	Three inclined side strips double layers
		BS2-4	2.12	-	2.42	One vertical side strip double layers

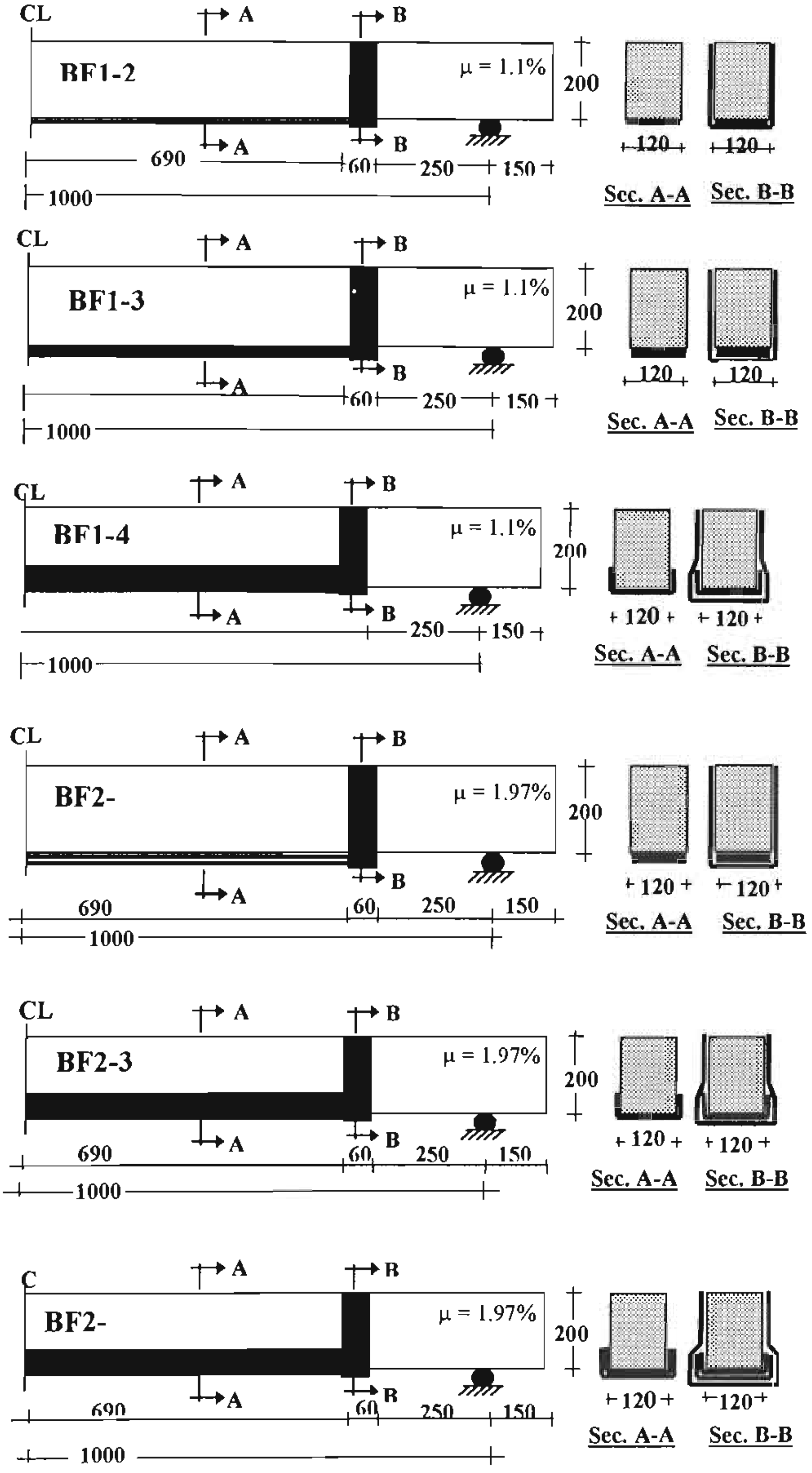

Fig (1) Strengthening Modes of Beams in Flexural Groups.

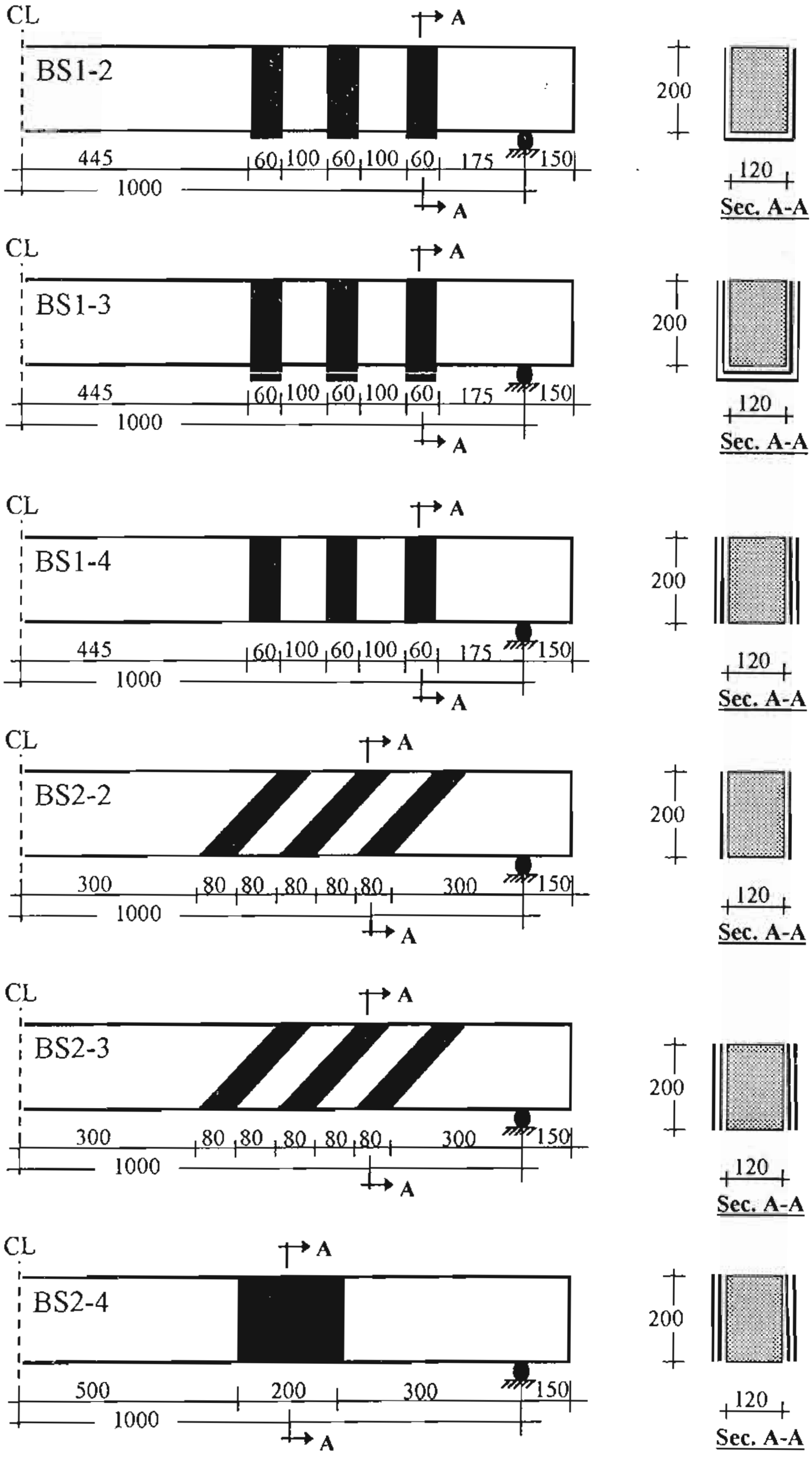

Fig (2) Strengthening Modes of Beams in Shear Groups.

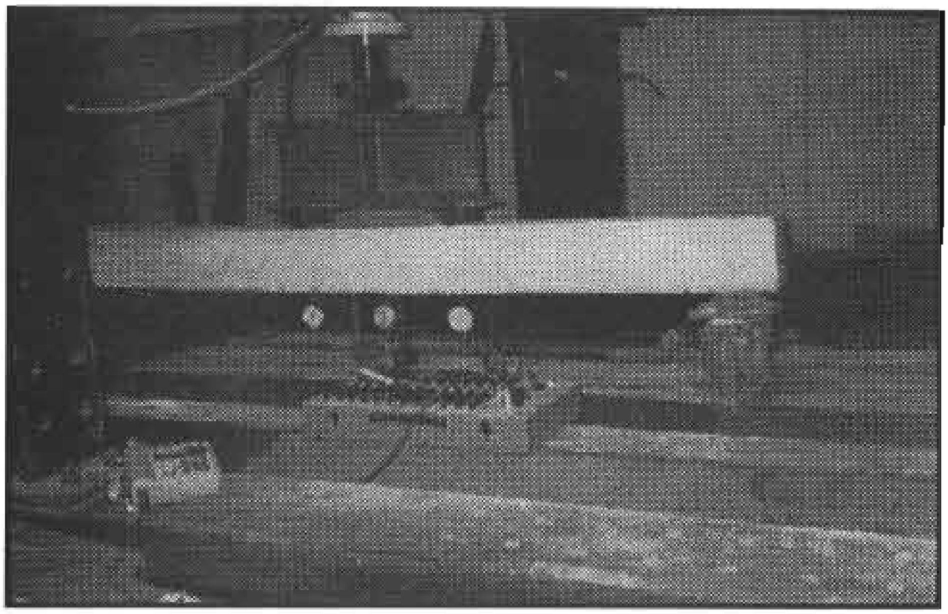

Fig. (3) Test Setup.

Table (2) Failure Load and Failure Mechanism of Beams in Flexural Groups.

Beam Number	Strengthening Mode	Cracking Load kN	Failure Load kN	Load Enhancement	Failure Mechanism
BF1-1	Control beam	30	50	Control	Yielding of tension steel followed by concrete crushing.
BF1-2	Single flat layer	35	60	20%	Yielding of tension steel followed by CFRP rupture.
BF1-3	Double flat layers	40	68	36%	Tension steel yielding followed by rupture of CFRP and concrete cover.
BF1-4	U-shape single layer	55	70	40%	Crushing of concrete in compression zone associated with steel yielding and CFRP rupture at midspan
BF2-1	Control beam	45	76	Control	Yielding of tension steel followed by concrete crushing.
BF2-2	Double flat layers	60	85	12%	Crushing of concrete in compression zone and debonding of CFRP sheet and concrete cover.
BF2-3	U-shape single layer	75	88	16%	Crushing of concrete in compression zone with yielding of steel and CFRP rupture at midspan.
BF2-4	U-shape double layers	80	100	31.6%	Crushing of concrete with steel yielding and CFRP rupture at midspan .

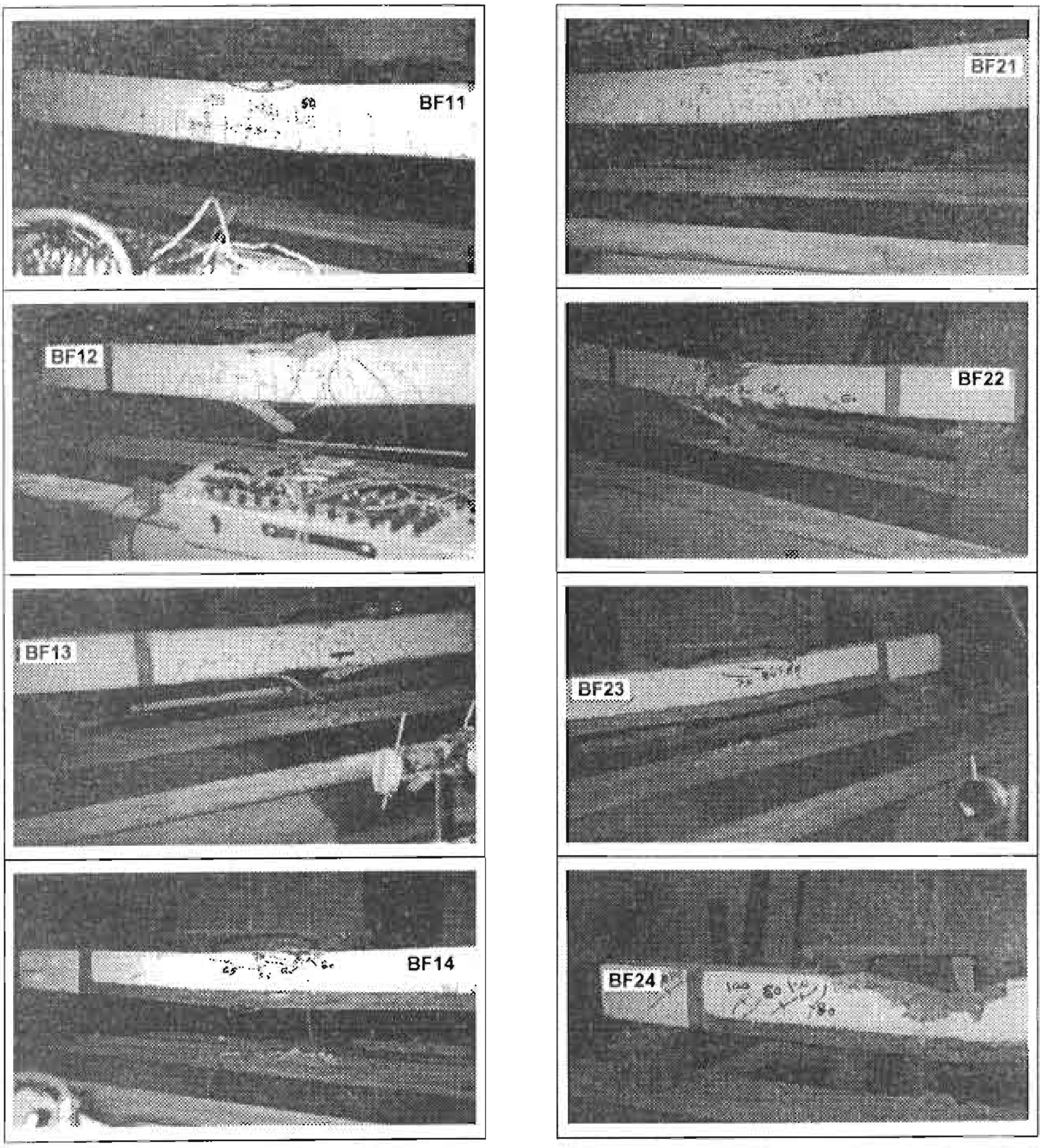

Fig. (4) Failure Illustrations of Different Beams in Flexural Groups.

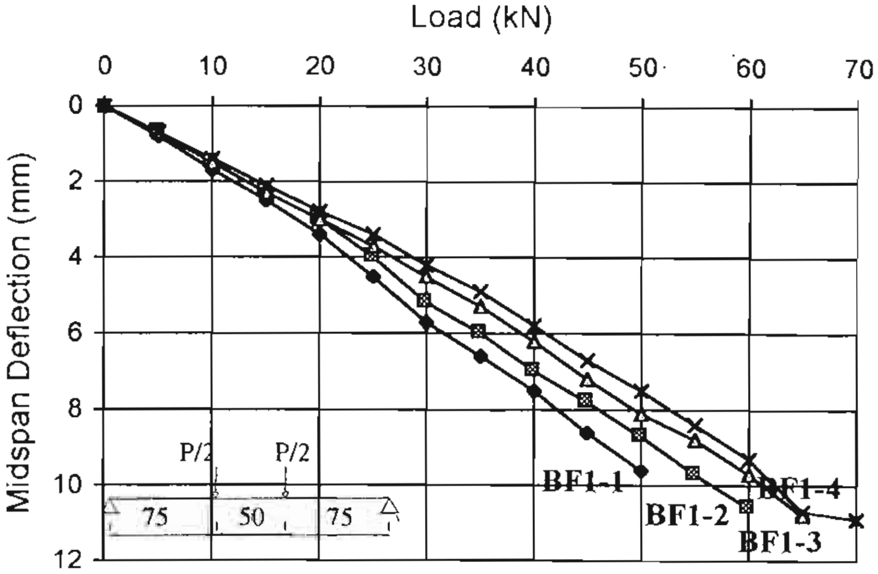

Fig.(5) Load–Deflection Relationship of Beams in Flexural Group (BF1).

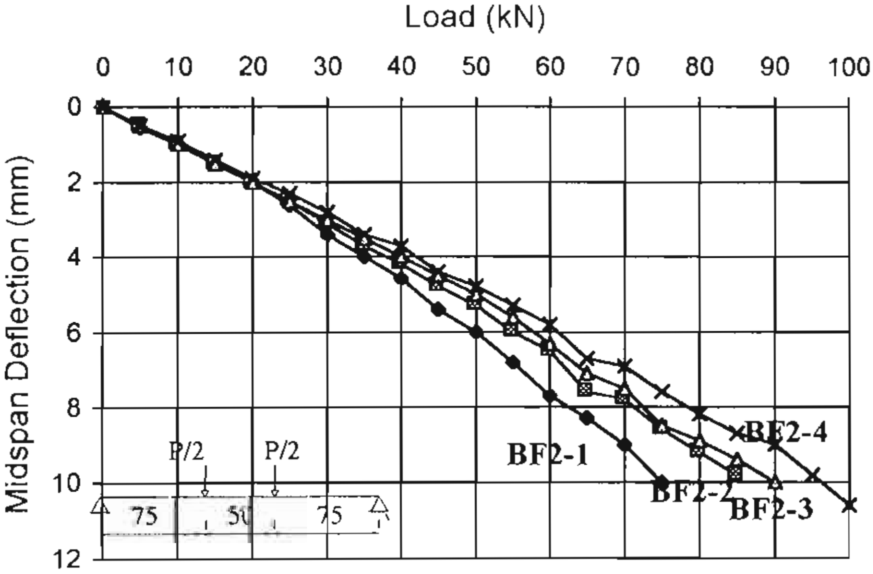

Fig.(6) Load–Deflection Relationship of Beams in Flexural Group (BF2).

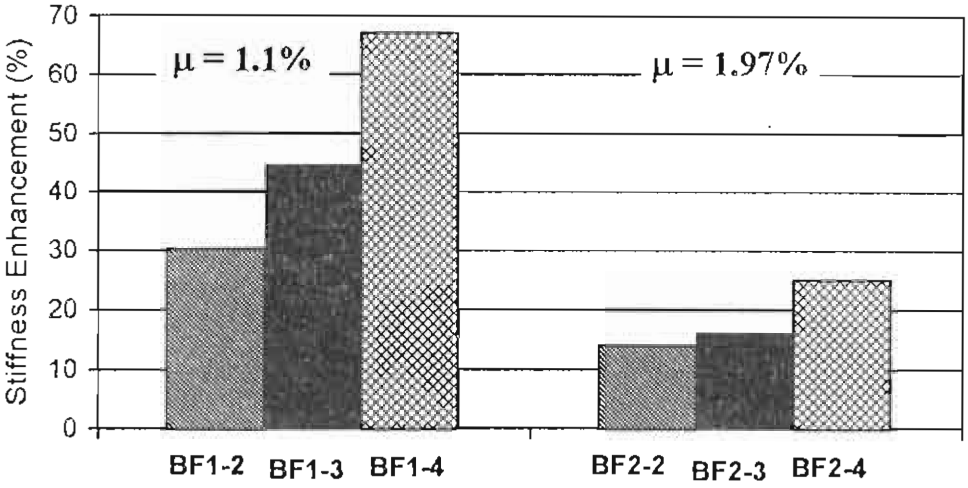

Fig. (7) Stiffness Enhancement of Beams with Flexural Srengthening.

Table (3) Failure Load and Failure Mechanism of Beams in Shear Group.

Beam Number	Strengthening Mode	Failure Mechanism	Failure Load kN	Load Enhancement
BS1-1	Reference (without strengthening)	Shear failure	90.0	Control
BS1-2	Three vertical U-shape single layer	Crushing of concrete in compression zone	102.0	13.3%
BS1-3	Three vertical U-shape double layers	Crushing of concrete in compression zone	112.0	24.4%
BS1-4	Three vertical side strips double layers	Crushing of concrete in compression zone	105.0	16.6%
BS2-1	Reference (without strengthening)	Shear failure	95.0	Control
BS2-2	Three inclined side strips single layer	Shear failure	125.0	31.6%
BS2-3	Three inclined side strips double layers	Crushing of concrete in compression zone	145.0	52.6%
BS2-4	One vertical side strip double layers	Shear failure	105.0	10.5%

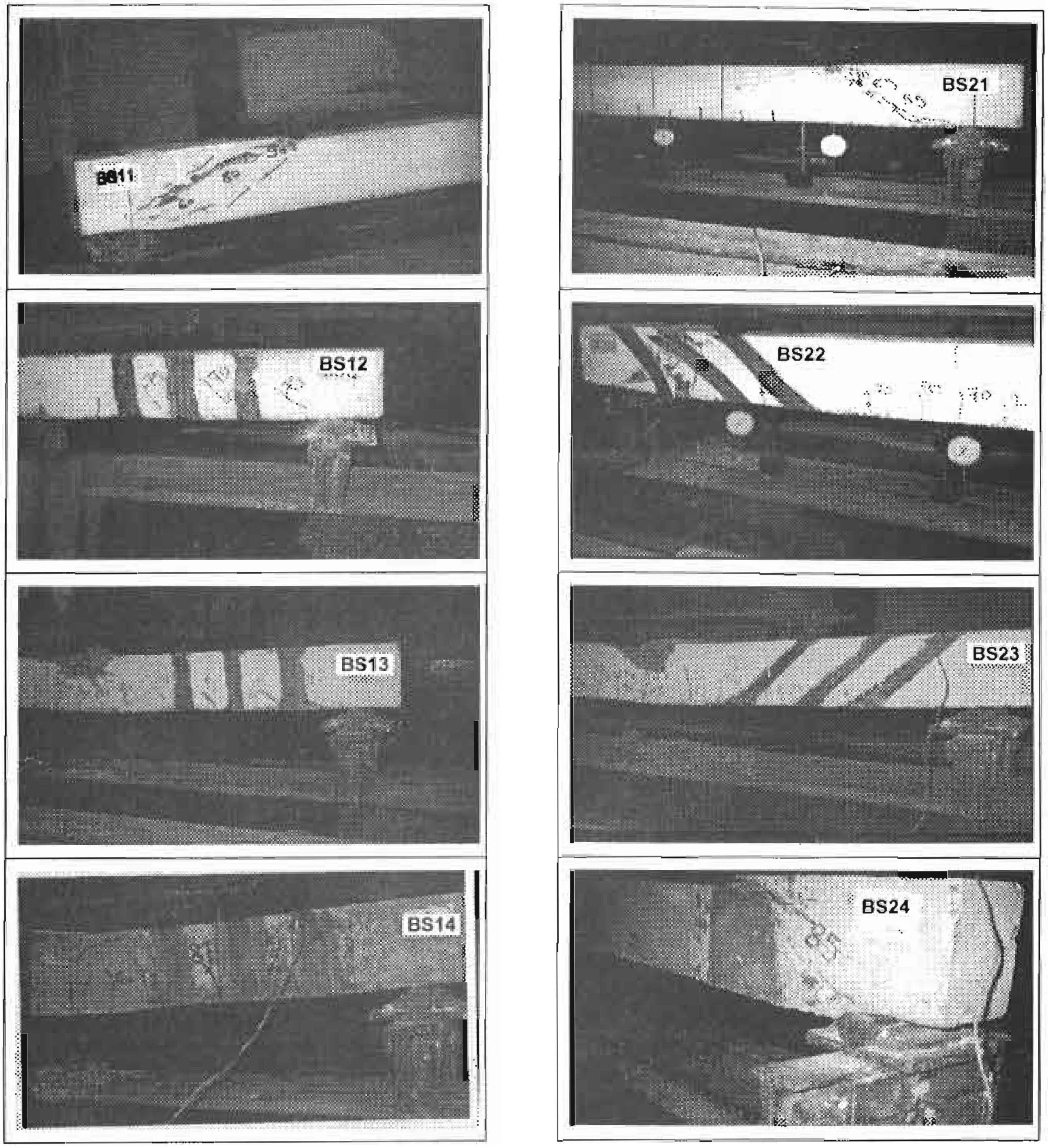

Fig. (8) Failure Illustrations of Different Beams in Shear Groups.

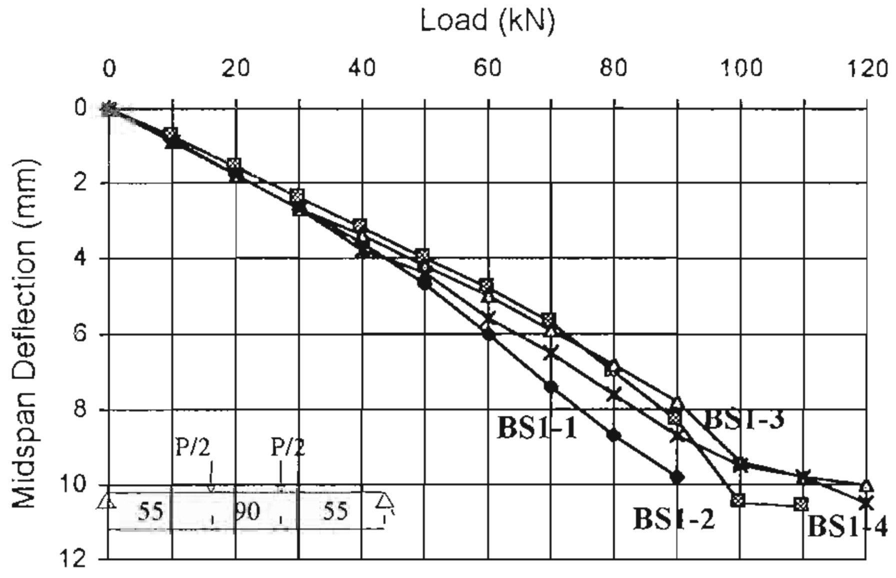

Fig.(9) Load–Deflection Relationship of Beams in Shear Group (BS1).

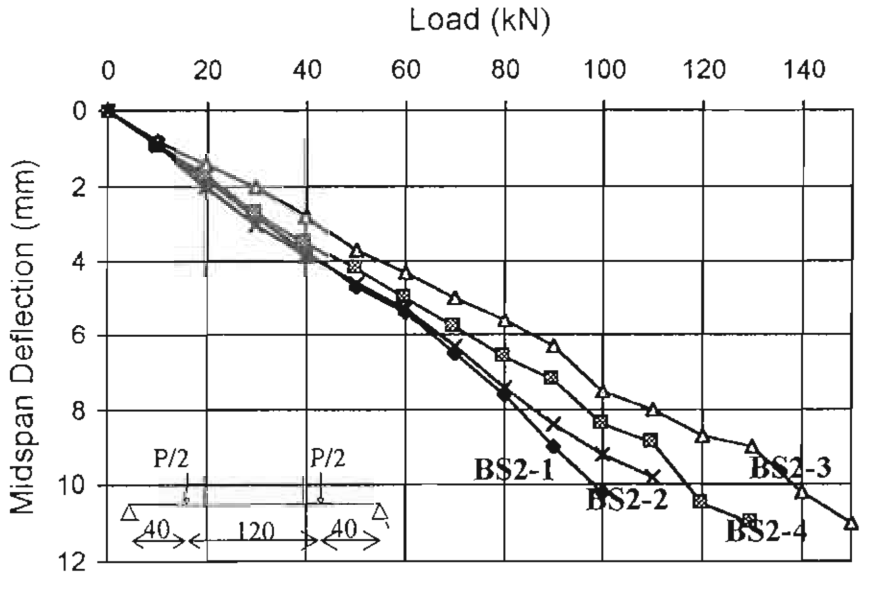

Fig.(10) Load–Deflection Relationship of Beams in Shear Group (BS2).

Table (4) Stiffness Enhancement due to Shear Strengthening.

Beam Number	$\frac{a}{d}$	Failure Load kN	Load at $\Delta = 5$mm kN	Stiffness Enhancement %
BS1-1	3.33	90.0	53	Control Beam
BS1-2	3.33	102.0	63	18.87
BS1-3	3.33	112.0	62	16.9
BS1-4	3.33	105.0	56	5.7
BS2-1	2.42	95.0	55	Control Beam
BS2-2	2.42	125.0	60	9
BS2-3	2.42	145.0	70	27.3
BS2-4	2.42	105.0	59	7.3

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