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Behavior of Prestressed Concrete Non-Prismatic Double Tee Beams

تصرف العتبات مسبقة الاجهاد ثنائية الجذع غير الموشورية

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Abstract

One advantage of using prestressed concrete structural elements is the control of deflection under normal service load levels. Prestressing permits the use of smaller cross-sections by keeping the section uncracked through design load levels. Also, an uncracked section is particularly desirable where exposure to a corrosive environment is a factor of concern.

In the present study, experimental test results are presented for three non-prismatic prestressed concrete beams. The chosen beam shape was the double tee beam, for its wide applicability and in situ performance. The chosen beams had different span length, geometric ratio, amount of prestressing area, loading arrangement and procedure for applying the load.

All the tested beams have been cast in the same circumstance in which they were designed to function. The first beam was cast during the time of the present research, and the others were being on storage. The last two beams have been chosen from groups of storage beams, to satisfy the objective of the research. Those beams were fabricated at **Al-Rasheid State Contracting Company** and were tested in its labs.

الخلاصة

منحت العتبات مسبقة الجهاد ميزات عديدة في مجالات مختلفة من تطبيقات الهندسة المدنية و خاصة في سيطرتها و تحكمها بمسألة الهطول إثناء التحميل و تحديداً الأحمال الخدمية. كذلك سمحت طريقة العتبات مسبقة الإجهاد باستخدام مقاطع صغيره نسبياً مع المحافظة على المقطع خالي من التشققات إثناء تحميل الحمل التصميمي.
تضمن هذا البحث أجراء تجارب عملية حقلية على ثلاث عتبات خرسانية غير الموشورية مسبقة الإجهاد ثنائية الجذع مع الأخذ بنظر الاعتبار التنويع بطبيعة العتبات المفحوصة بحيث توسع نطاق الدراسة. وعلى سبيل المثال اختلاف أطوال العتبات المفحوصة و نسب إبعاد المقاطع مع الطول و الكميات التسليح بأنواعه و كذلك الأحمال المسلطة و طريقة تسليطها.
تمت الفحوصات العملية في المعامل الإنتاجية لشركة الرشيد العامة للمقاولات المحدودة. حيث أجريت الفحوص تحت ظروف تجاري الظروف المصممة لها. تم اختيار عتبة مسبقة الإجهاد ثنائية الجذع أنتجت في وقت الفحص و عتبتان تم اختياريهما من خزين الشركة لتحقيق غرض البحث.

Experimental Program

The present experimental program was conducted at the laboratories of Al-Rasheed State Company for Constructional Contracts. The specimens chosen to be tested experimentally were typical production full scale double tees having total length of 13, 18, and 20.7m, representing similar units used in practice as roofing. The double tee beams examined in this study were 425, 550, and 482.5 mm deep over the support and 750, 1000, and 1000 mm deep at mid span respectively. The beams had web width of 120 mm and flange width of 2380 mm. For all of these beams, the slope of descend of top surface is 1/20. General elevation and beam cross-section are shown in Fig. (1) [2].

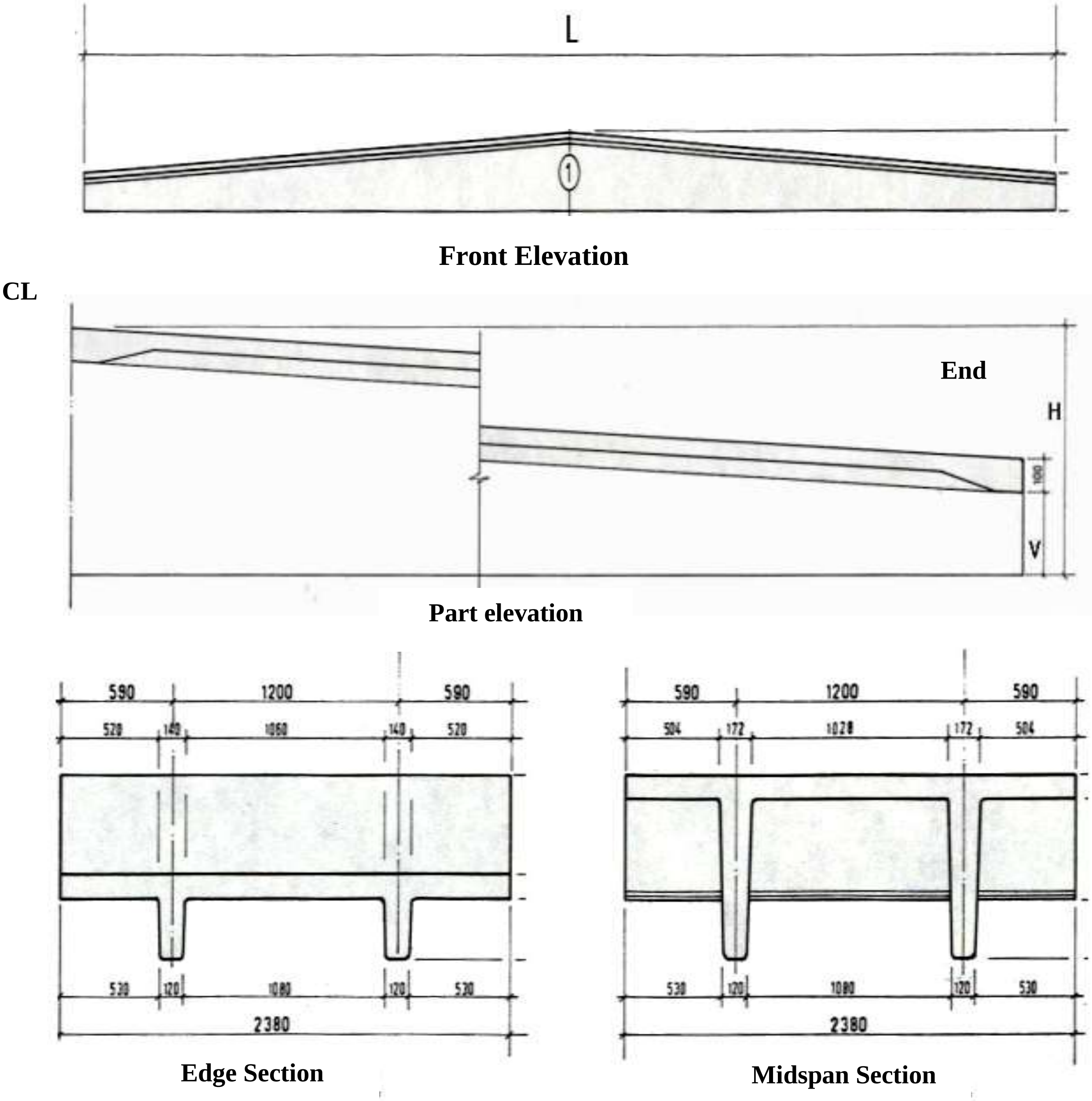


Fig. (1). General shape of the chosen double tee beams

The beams were designed to span 12.520, 17.520, and 20.220 m support to support. Flange and web mild steel reinforcement consisted of welded wire fabric with prestressing strands located in the webs.

The present work has been done with the support of **Al-Rasheed Company** using their facilities. This has put many limitations on the details of the work. First, types and dimensions of the tested beams were limited to those available as products of the company or those desired to be tested in specific by the company. For a short beam, a 13 m non-prismatic beam was chosen form the products of the company noting that the company produces no shorter prestressed beam. The aforementioned beam was tested up to failure. On the other hand a 20.7 m non-prismatic double tee was tested and meant to represent a long-span beam. No such spans are covered by prismatic beams from the products of this company. The maximum span of prismatic beams produced by the company is 18m. This non-prismatic beam was tested up to failure, too.

Materials

The concrete used for all specimens consisted of ordinary Portland cement, coarse aggregate, and fine aggregate. Central mixing machine was used in the factory where the tested beams have been fabricated. A mix of C40-C43, with a water-cement ratio of 0.45 was used for all tested beams [3].

Generally the specified concrete strength at release was 35MPa and at 28days was (40-43MPa) indicating by taking a cylinder specimen on the cast time. The beams were cured following the PCI manual for quality control for plants and production of precast prestressed concrete products by using either steam curing or oil boiler for 12-16 hour on 30^{o}C.

The taken samples indicate concrete density of 2420 kg/m3, with settlement equal to 80mm on measured temperature equal to 38^{o}C.

The cement that has been used in the tested beams was produced in Al-Kubasa factory, which is commonly used in production the double tee items. The fine and coarse aggregates have been tested by the National Center for the Construction Laboratories; Table (3.1) shows the fine and coarse aggregate sieve analysis [3].

The prestressing strands were seven-wire 12.7mm diameter, with cross-sectional area of 92.6mm2 and characteristic load of 164kN. These strands were initially stressed up to about 123kN per strand. According to the American Standard Specification ASTM A416, the laboratory test for the used strands indicated a rupture force of 186kN [3].

Additional longitudinal mild steel bars placed along beam span used to hold the prestressing wires and the vertical stirrups consisted of 10mm bars. According to the American Standard Specification ASTM A416M, the laboratory test for these bars indicated a yielding stress of 650N/mm2 and a rupture stress of 709N/mm2, and the elongation was 10.5%. The tested sample succeeds on the inclination with an angle 180o. Mild steel stirrup reinforcement was placed at the ends of the members to arrest diagonal cracking resulting from prestressing force developed [3].

A mesh of welded wire fabric was used to reinforce the flange which was weighted 2.495 kg/cm2. According to the American Standard Specification ASTM A82/8S, the laboratory test for these mesh indicated an ultimate tension stress of 602N/mm2 in one direction and 646N/mm2 in the other direction [3].

Table (3.1) Fine and coarse aggregate test results

	Sieve No.	% Passing	% passing Standard	Standard Specification
Sand	10	100	100	Iraqi Standard Specification 45 in 1984
	4.75	90	90-100	
	2.36	77	75-100	
	1.18	56	55-90	
	0.6	37	35-59	
	0.3	26	8-30	
	0.15	3	0-10	
Passing Sieve 0.75		2.5	5 up limit	
So_3 %		0.16	0.5 up limit	

	Sieve No.	% Passing	% passing Standard	Standard Specification
Gravel	75	100	100	Iraqi Standard Specification 45 in 1984
	63	100	100	
	37.5	100	100	
	20	58	95-100	
	14	37	-	
	10	12.5	30-60	
	5	0	0-10	
Passing Sieve 0.75		0.2	3 up limit	
SO_3 %		0.08	0.1 up limit	

Test Setup

The first beam tested was non-prismatic partially prestressed double tee beam with a span of 18.0m, designated as B1 tested under service load condition. The second was non-prismatic fully prestressed double tee beam with span of 20.7m which has been identified as B2 tested up to failure. The third tested beam was 13.0m span non-prismatic partially prestressed double tee beam, which was identified as B3 tested up to failure. Full details funded in reference [4].

Structural steel support was fabricated to provide a simply supported condition. These supports held the beam approximately 800 mm above the ground level so the double tee could freely deflect.

Prior to the test, the beams were instrumented with four dial gages to measure vertical displacements. Gages were installed at beam midspan (gages A and A̲) and 0.25Lm far from each support (gages B and C). The dial gages used had 25 mm stroke and 0.025mm accuracy. For beam B2 and B3, the gages being inefficient to continue the test up to failure, so alternative measuring by means of a theodolite and a vertical ruler coupled with an indicator were used.

During each test, the displacements were measured at two positions "close to supports and quarter span" for the tested beam. Fig (3) shows a typical dial gage installation.

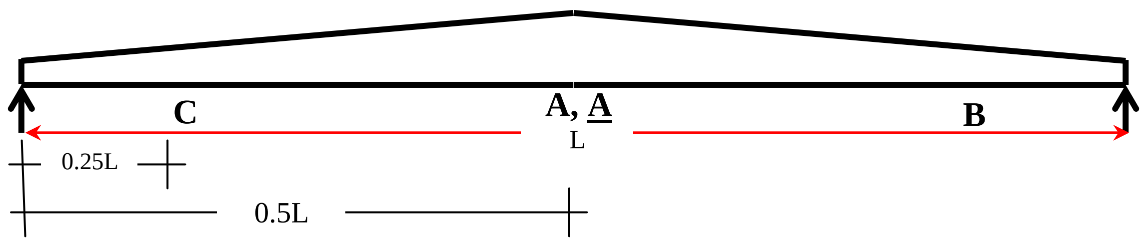


Fig. (3). Typical dial gages instillation.

Non-prismatic double tee beams are widely used in roof applications, on that base, the loading arrangement was chosen to be uniformly distributed loads. For beam B1, the loads were distributed along its span length, while for the case of beam B2 and B3; the loading was uniformly distributed along the central part of the length span, to increase the bending failure probability. Figure (4) shows the loading process and test setup.

Applied loads

All beams were subjected to uniformly distributed load along the span length. Large concrete blocks measuring 0.3×0.25×2.4 m and weighting 4.20kN each, were used to simulate the quasi-uniform loading condition.

Fig. (4) General test setup for the tested non-prismatic beams [3]

Tested beam under service loads

In this part from the research the chosen beam B1 was tested under service loads as shown [4]:

1. Description of Beam B1

The test specimen was a 2380 mm wide beam, 550mm deep at the support and 1000mm at midspan. The double tee cast with normal weight concrete and was designed for a fully precast roofing structure application. The member length was 18m for which the flange was 60mm thick and cast monolithically with the legs. The nominal concrete strength at 28days was 40MPa, which is commonly used in the plant's concrete marketing area. The design service load was 2.8 kN/m^2. Section properties are shown in Fig. (5) and listed in Table (2).

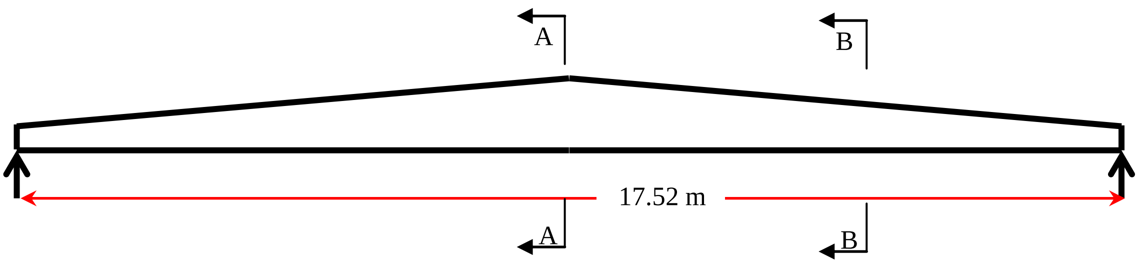
The specimen contained ten wire strands 12.7mm in diameter, Grade 270, low relaxation initially stressed to 115kN. The legs of the double tee contained eight mild steel 10mm in diameter, with vertical stirrups 6mm in diameter with equal spacing of 250mm along the leg. The flange was reinforced with welded mesh fabric. The beam was tested under service loading condition to check its compliance to the ACI code acceptance requirements regarding deflection and deflection recovery.

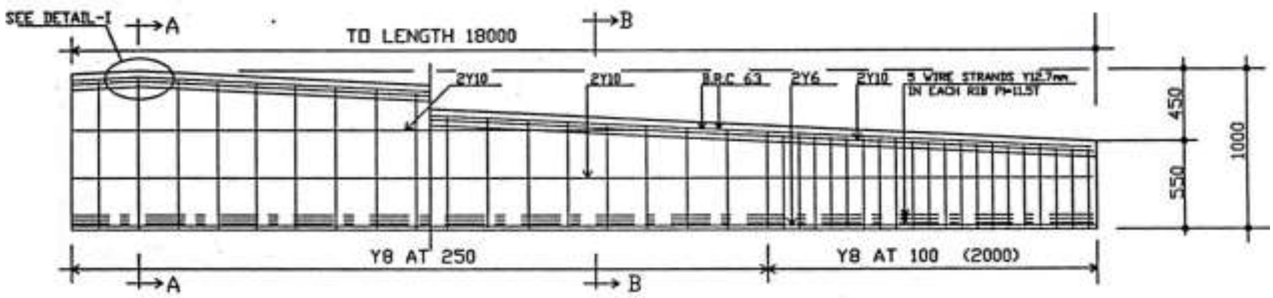
2. Test procedure

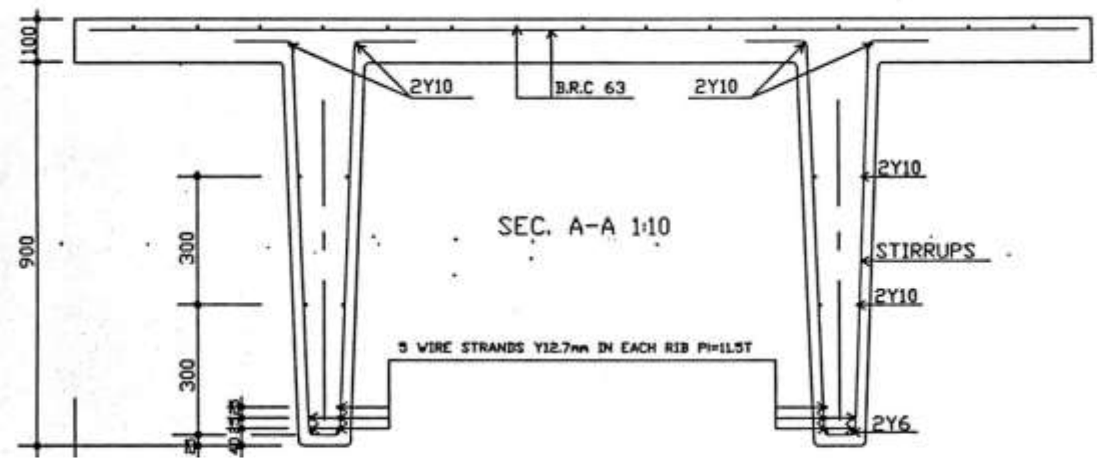
The test was performed over a four-day overall period in accordance with Chapter 20 of the ACI 318-02 Building Code [1]. A 3.75kN/m^2 uniformly distributed load was applied along the beam top surface, without causing any shock on the beam. This load represented the superimposed dead load, as shown in Fig. (6). The specimen left with this load for 48 hours without any external effect. Later the dial gages were installed and some notes were recorded on the beam behavior, as shown in Fig. (7). Then, the beam was loaded with additional uniformly distributed test load of 2.8kN/m^2 which represented the live load as in Fig. (8). The loading procedure was applied in four stages. At each stage, the deflection was read and notes were recorded. The specimen again was left for 48 hours under this loading condition, and the overall deflection was recorded. After that, the testing load 2.8 kN/m^2 was released, and the beam left for 24 hours to get the final deflection recovery.

Table (2). Beam B1 - Section Properties

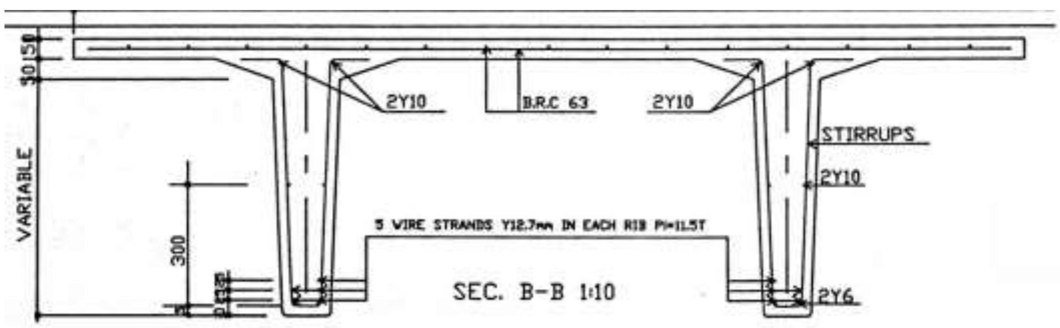
Beam 18m span	Dimension (mm)				Area mm^2	I × 10^9 mm^4	Z$_{top}$× 10^3 mm^3	Z$_{bot}$× 10^3 mm^3
	Depth	**Width**	**Y_t**	**Y_b**				
Support edge	550	2380	158.43	391.56	279197	14.5	91523	37031
midspan	1000	2380	320.3	629.68	417032	45.5	14205	72258







Sec. A-A at Midspan



Sec. B-B general section.

(All dimensions not indicated are in mm)

Fig. (5). Beam B1 – Elevation and Section Properties [3]

Fig. (8). beam B1 – Arrangement of the total uniformly distributed loads.

Fig. (6). Beam B1 – Arrangement of the uniformly distributed superimposed dead load

3. Test Results

Deflections obtained at midspan and at regions close to support are summarized in Table (3). Besides recording the deflections, the double tee beams were visually monitored for distress throughout the load test. Application of the superimposed dead load and the first stage of the test resulted small horizontal non-structural hair crack the junction of web and in flange intersection, and on the web at regions close to the support. These cracks stay in their form without propagation during the loading progress. During application of the next loading increments, flexural hair cracks were observed at midspan.

Table (3). Beam B1 - Deflection variation during the loading progress[3]

Gage No.	Deflection (mm)						
	Before applying testing load	**After applying 25% of testing load**	**After applying 50% of testing load**	**After applying 75% of testing load**	**After applying full testing load**	**After 48 hours from applying full testing load**	**After 24 hours from releasing testing load**
A	0.0	2.7	9.3	13.8	20.1	28.6	6.2
A	0.0	2.7	9.8	13.5	22.1	29.9	5.9
B	0.0	1.2	1.7	3.5	5.4	7.4	2.9
C	0.0	1.25	3.6	4.3	5.34	6.3	2.7

Acceptance criteria for the beam following the test were based on permissible deflection and deflection recovery. As specified in Chapter 20 of the ACI 318-02 Building Code [1], the maximum vertical deflection and the deflection recovery shall not exceed the following:

$$\text{Maximum deflection} \leq \frac{L_t^{\,2}}{20000h} \tag{3.1}$$

$$\text{Deflection recovery} \leq \frac{\text{Maximum deflection}}{4} \tag{3.2}$$

where L_t is the beam test span length and h is the beam height. If the maximum deflection exceeds this value, deflection recovery within 24 hours after test load removal shall be grater than 80% of the total deflection. Hence, deflection reading recorded during the test provided the basis for acceptance of the double tee beams. Because vertical deflections at midspan exceeded maximum deflection stated into Eq. (3.1) above as indicated in Table (3.3) in Gage A, and A (28.6 and 29.9mm respectively), it was necessary to take the deflection recovery in consideration. After the test load was left in position for 24 hours, deflection readings were recorded and the test load was removed. The recovery deflection was 6.2mm and 5.9mm at gages A, and A, respectively, as shown in Table (3.3). For both gages, the reading deflection recovery was less than the value indicated by Eq. (3.2) for test load sustained over 24 hour time period. Figure (3.9) shows the load-defection curve obtained for this beam.

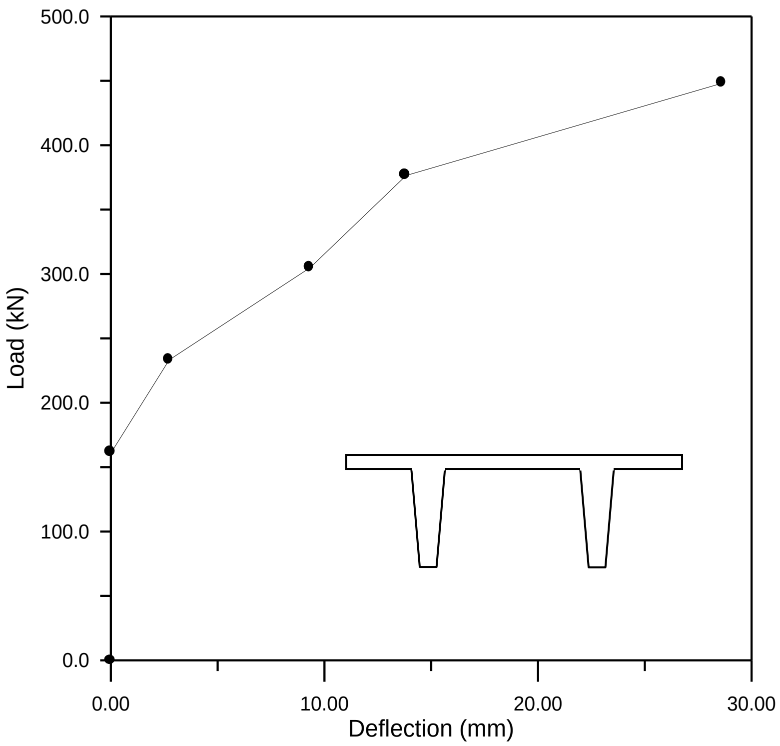


Fig. (9).Beam B1 –Total load- Midspan deflection response.

Since the required deflection recovery was realized immediately following test load removal, further load testing was discontinued. In terms of ACI structural strength requirements, the tested double tee beam performed satisfactorily.

As stated previously, flexural hair cracks developed at midspan. After applying all test loads, the cracks were observed extending from the bottom web surface to the flange-web junction. Cracks in this region were typically less than 0.25mm in width. After removal of the test load, the cracks were closed and were no longer visible.

Tested beams up to failure

Herein, two beams have been chose to be loaded up to failure and their behavior were supervise and examined as shown. Full details and more indicated information funded in reference [4].

1. Description of Beam B2

The tested beam B2 was identical in cross sectional dimensions with beam B1. Depth of the beam was 1000mm at mid-span and 482.5mm at supports. Total beam length was 20.7m retaining the same descend slope of 1/20. This beam was drawn from a number of stored units with the mentioned dimensions and it was designed for a fully precast roofing application. This sample was supported by an I-section of 250mm flange width. The flange thickness of the beam was 60 mm monolithically cast with the legs. The nominal concrete strength at 28days was 45MPa, which is commonly used in the plant’s marketing area. Section properties are given in Fig. (10) and listed in Table (4) **[3]**.

The specimen contained fourteen wire strands 12.7mm in diameter, Grade 270, low relaxation initially stressed to 115kN arranged equally per ribs. The legs of the double tee contained twelve mild steel bars (eight of them was of 10mm and four of 6mm in diameter), with vertical stirrups 6mm in diameter divided equally along the leg. The flange was reinforced with welded mesh fabric.This time, testing of the beam was continued up to failure.

2. Description of Beam B3

The test specimen consisted of 2380mm wide flange. Depth of the cross section was 425mm at supports and 750mm at midspan. The beam cast with normal weight concrete and was designed for a fully precast roofing structure application. The member length was 13m. The flange was 60mm thick and cast monolithically with the legs. The nominal cube concrete compressive strength at 28days was 41kN/m^2. Section properties are given in Fig. (18) and listed in Table (4). Figures (19) and (20) show the test procedure **[2]**.

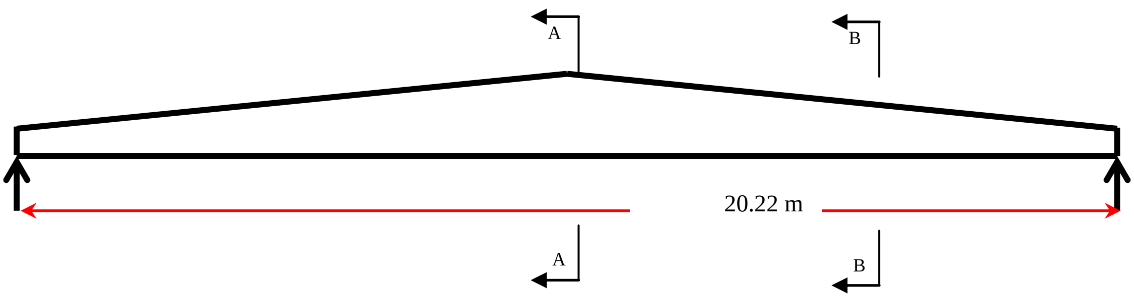
The specimen contained six wire strand 12.7mm in diameter, Grade 270, low relaxation initially stressed to 115kN arranged equally per ribs. The legs of the double tee contained twelve mild steel (eight of 10mm and four of 6mm in diameter bars), with vertical stirrups 6mm in diameter divided equally per leg. The flange was reinforced with welded mesh fabric B.R.C 63. The beam has been tested up to failure.

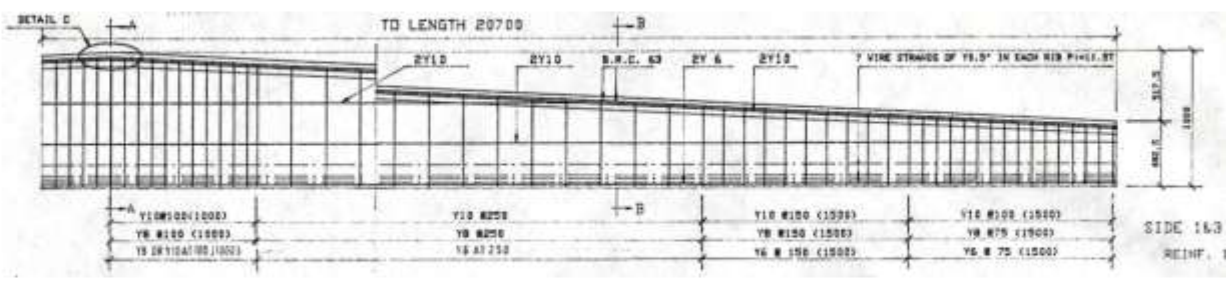
3. Test procedure

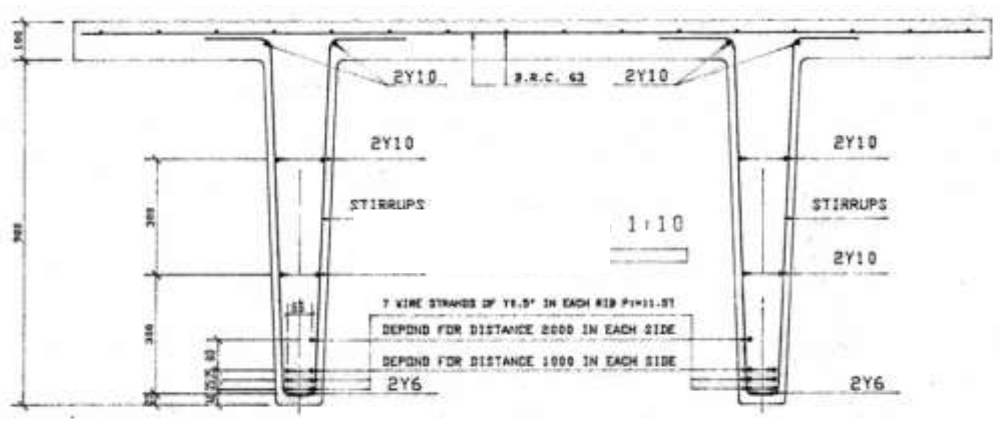
The test was performed over a two-day period. The beam was subjected to a progressive increasing load while deflections at each increment of loading were recorded by applying a single or a couple of loading blocks. The loading was applied to the middle part of the beam ending 5.5 m away from the supports as shown in Figs. (11 to 14). This was a measure to increase likelihood of bending failure.

Table (4). Beam B2 - Section Properties

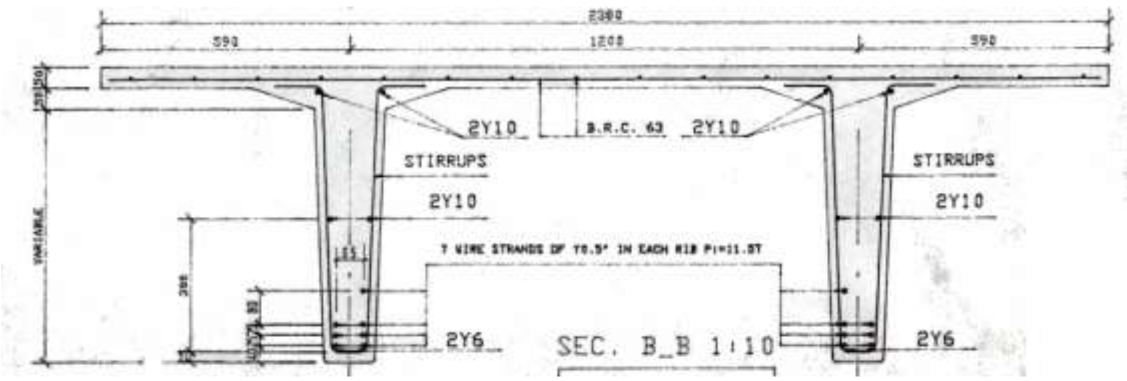
Beam TT 20.7m span	Dimension (mm)				Area mm^2	I×10^9 mm^3	Z $_{top}$× 10^3 mm^3	Z $_{bot}$× 10^3 mm^3
	Depth	Width	Yt	Yb				
Support edge	482.5	2380	133.64	348.86	258328	11.5	86052	32964
midspan	1000	2380	341.47	658.52	435967	51.97	15219	78193







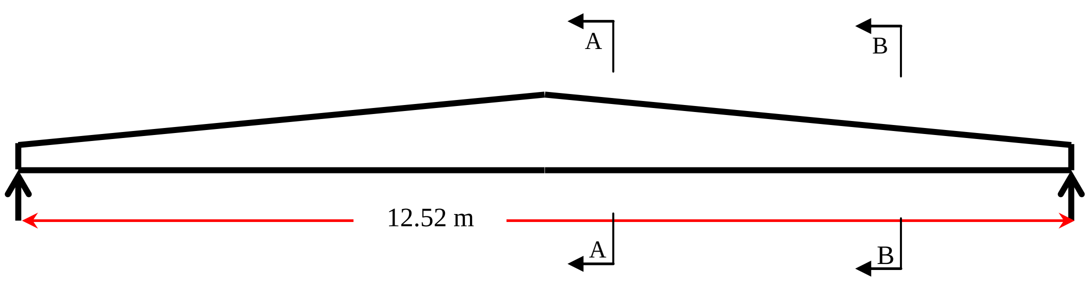
Sec. A-A at Midspan

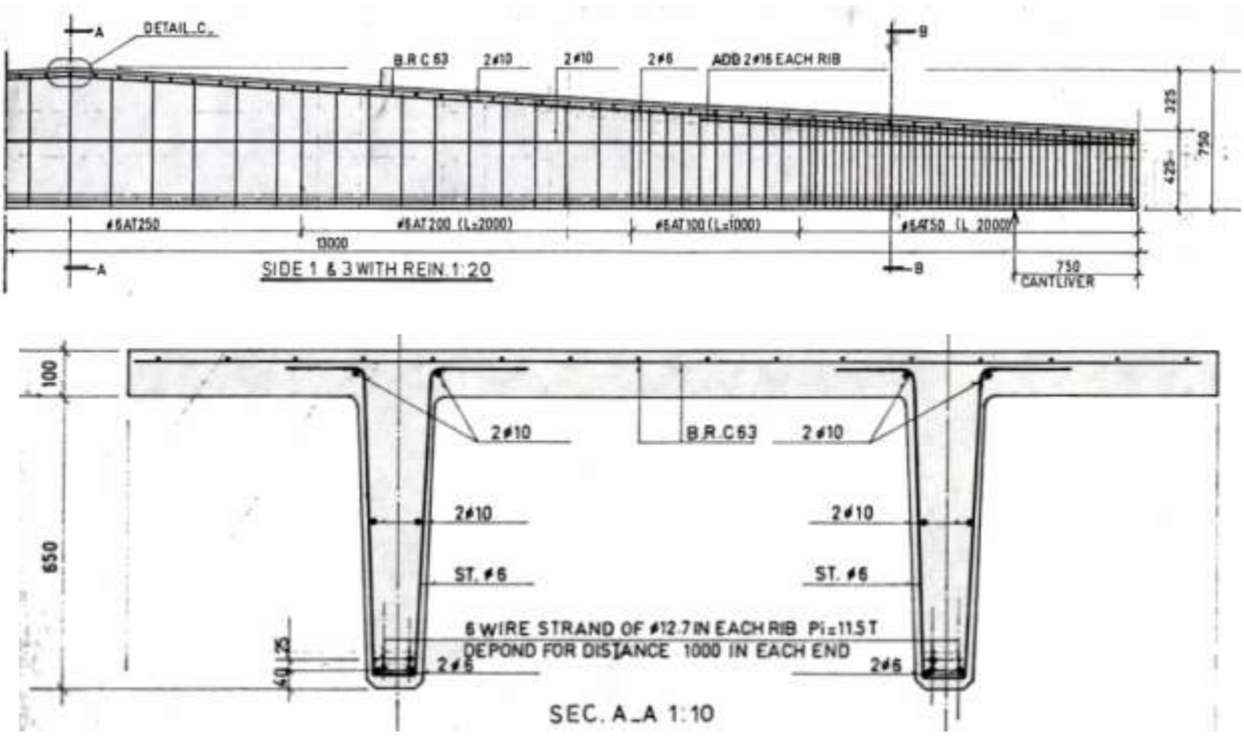


Sec. B-B general section.
(All dimensions not indicated are in mm)
Fig. (10). Beam B2 - Elevation and Section Properties.

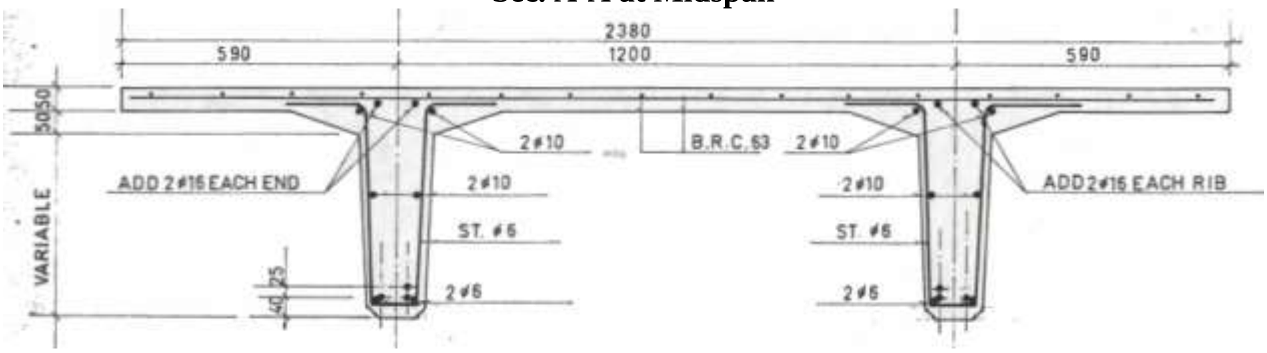
Table (4). Beam B3 - section Properties

Beam 13m span	Dimension (mm)				Area mm^2	$I\times10^9$ mm^4	$Z_{top}\times 10^3$ mm^3	$Z_{bot}\times 10^3$ mm^3
	Depth	**Width**	Y_t	Y_b				
Support edge	425	2380	113.56	311.43	241097	6.28	55301	20165
midspan	750	2380	512.85	237.14	345083	19.07	37184	80416





Sec. A-A at Midspan



Sec. B-B General Section.

(All dimensions not indicated are in mm)

Fig. (18). Beam B3 - section Properties [2]

Fig. (11). Beam B2 – General view before testing.

Fig. (12). Beam B2 – Arrangement of the applied loads.

Fig. (13). Beam B2 – Procedure of imposing the applied loads

Fig. (14). Beam B2 - Setting the deflection measuring tools.

Fig. (19). Beam B3 – Arrangement of the applied loads.

Fig. (20). Beam B3 - Setting up the dial gages

4. Beam B2 - Test Results

Displacements were measured at both ends and at the center of the span for the tested beam throughout the entire range of loading. Figure (15) shows the deflection progress with increasing the applied load recorded using the midspan dial gages and measurement instruments.

Besides recording the deflections, the double tee beam was visually monitored for distress throughout the load test. Small horizontal non-structural cracks were already appeared close to the flange-rib intersection. These hair cracks did not propagate during the progress of the test.

Flexural cracks were observed first at midspan. These cracks initiated at beam bottom face and propagated upward with increasing load. The flexural cracks become wider and wider until flexural failure. All cracks that appeared were recorded. The using of small steps of loading (by applying blocks at relatively small increments) has a significant effect on reading the deflection and monitoring the cracks. Each crack was indicated with a number equals to the stage of loading. In the same way, the development of that crack was re-indicated. Figure (16) and (17) represents the sequence of crack propagation.

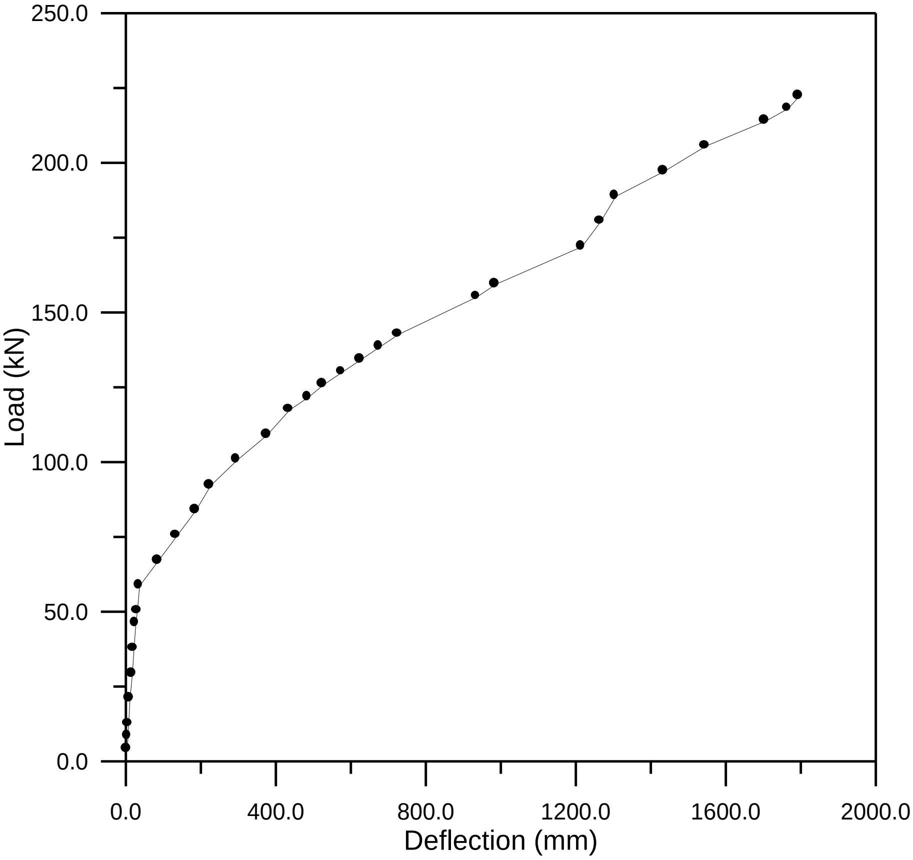


Fig. (15). Beam B2 – Total load- Midspan deflection response.

Clearly shown from Fig. (15) that the stage of elastic behavior has been terminated at the first cracking load which equals to 68kN, which represent 30% of ultimate carrying load that equals to 222kN. The stage followed the cracking load was accompanied with crack propagation which increase in width as the applied load is increased. The failure finally occurs at a distance equal to 26% from the total beam length measured from the support.

According to the crack propagation, the applied loads were divided into seven increments relatively to crack developments. Figure (16) draw on that base, where the crack indicated according to the loading increment set close to it, with the inclination recorded in test time.

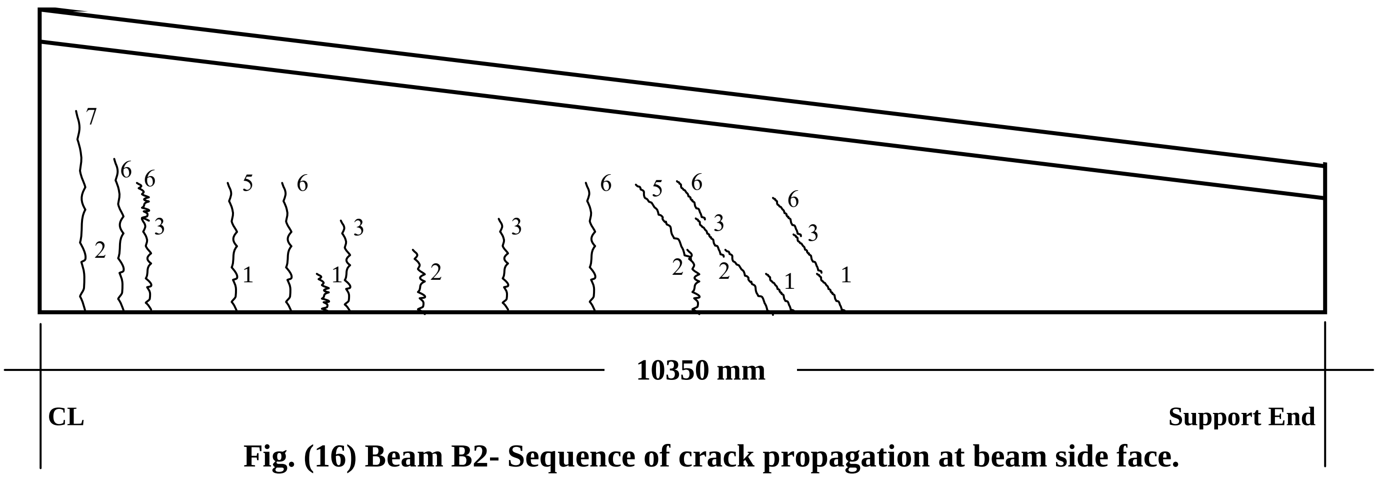
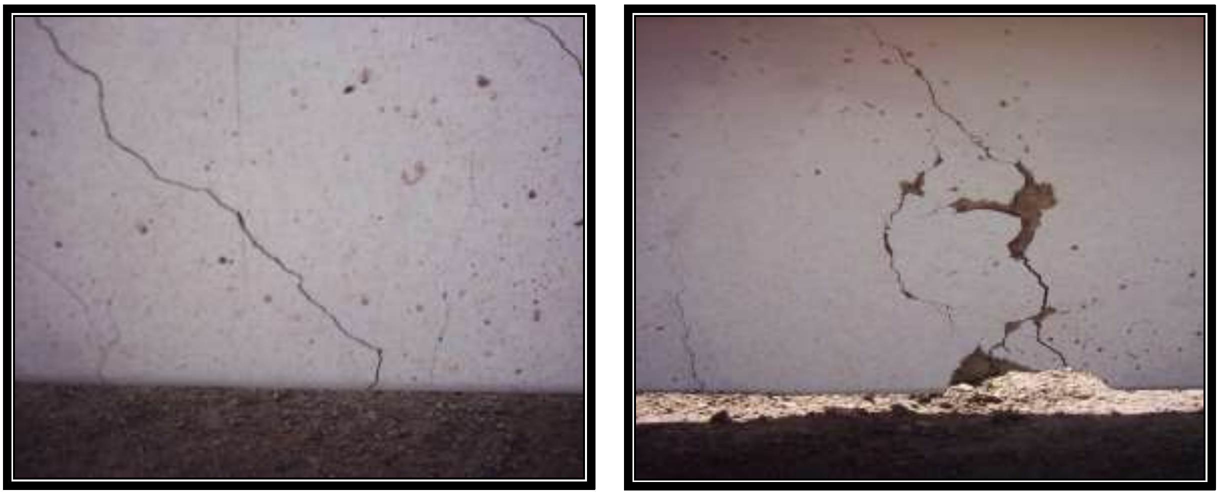


Fig. (16) Beam B2- Sequence of crack propagation at beam side face.



a. First crack appeared at 26% of the total beam length measued from the support

c. Final crack appeared at 26% of the total beam length measued from the support

Fig. (17. Beam B2- Crack propagation on beam face side.

5. Beam B3 - Test Results

Displacements were measured at both ends and at the center of the span during the test. Figure (21) shows the load-midspan deflection curve.

These hair cracks did not propagate during the progress of the testing. Flexural cracks were observed first at midspan, which propagate upward with increasing the testing load. The flexural cracks become wider until flexural failure as shown in Fig. (22).

Three distinct stages of behavior could be identified as, stage 1 which corresponds to the uncracked state of the beam when it behaves as a linear elastic member. This elastic behavior stage is terminated by onset of cracking at the pure bending zone at a load level of 116kN. The cracking load represents about 47% of the ultimate load that equals to 245kN.

Stage 2 followed and continued by the new cracks that were propagated in succession with an increase in the applied load. Such cracking reduces the beam stiffness, but the load deflection curve remains essentially a straight line indicating elastic response of cracked sections.

Stage 3 is characterized by a rapid decrease in the slope of the load deflection curve with slight increase of load levels. It commences with the formation of a plastic hinge, and since the beam was simply supported, theoretically the beam should continue to deform at the same load until the rotation capacity of the plastic hinge is exhausted. However, this beam exhibited slight increase in the applied load after yielding of steel had occurred.

The final failure cracks were indicated at a distance equals to 24% from total beam length measured from the support. Figure (22) shows first appear and final crack propagation indicated with increasing the load up to failure.

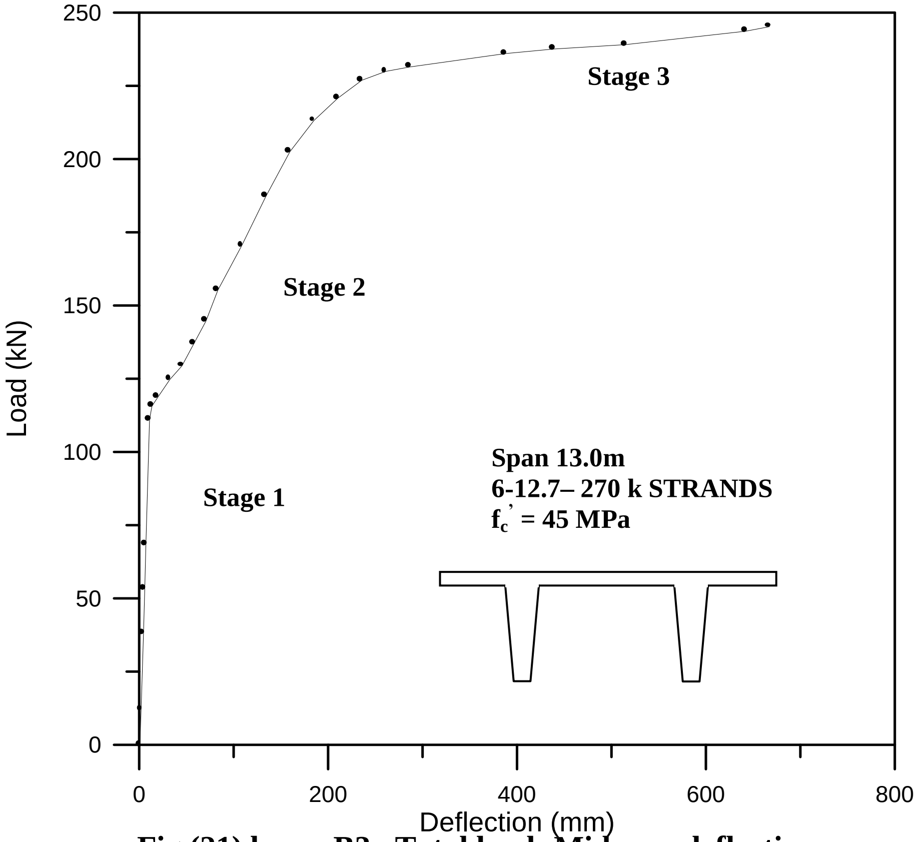


Fig.(21).beam B3 –Total load- Midspan deflection response.

Fig. (22). Beam B3- Crack propagation on beam face side.

Conclusions

In this section, the conclusions based on the experimental, and analytical studies carried out for various double tee beams with various loading conditions, and different states of prestressing, described in the previous chapters are given.

1- The experimental non-destructive test carried out for non-prismatic prestressed concrete double tee beam B1 indicated that the beam was accepted to be on function based on permissible deflection and deflection recovery, as specified in Chapter 20 of the ACI 318-02 Building Code.

2- The experimental tests carried out on beams B2 and B3 show the capability of the non-prismatic prestressed concrete double tee beams having short and long spans on carrying the expected loads. The cracking loads obtained for both tested beam were occurred at 30% and 47% of the ultimate load respectively. These ratios give a warning indication against failure, since the main function of the non-prismatic double tee beams is the application for roofing purposes.

3- Flexural failure of the non-prismatic beams B2 and B3 occurred at section located at 26% and 24% of the total length measured from the support respectively.

Future Suggestions

1. Experimental programs could be arranged to study the behavior and ultimate capacity of non-prismatic beams with high performance concrete.
2. Experimental work on simply supported non-prismatic double tee beams reinforced with carbon fiber sheets.
3. Experimental programs could be more precise by measuring the stresses on the concrete and on the other side on the strands wire.

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