STRENGTHENING OF CONCRETE ROOF USING CFRP STRIPS

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ABSTRACT

Carbon Fibre Reinforced Plastic (CFRP) strips were used for strengthening and control the deformation of existing roof panels at the North End Winnipeg Pollution Control Center (NEWPCC), Winnipeg, Manitoba. Changing industrial needs at the plant necessitates strengthening of the sixty years old concrete roof structure. The use of epoxy-bonded CFRP laminates was selected due to their characteristics of high strength, low weight, and easy to apply to the concrete surface. This technique introduced considerable saving in comparison to convential repair methods proposed for the same building.

This paper summarizes an experimental program conducted at the University of Manitoba to study the behavior of selected panels, removed from the existing roof structure. The first panel was tested to failure as a control specimen before applying the CFRP strips. The second and the third panels were tested after application of the CFRP strips. The test examined the various limit state behaviors including the ultimate capacities and failure modes. A model is presented to predict the behavior of the strengthened panels.

INTRODUCTION

Use of fibre reinforced polymer (FRP) has been established to be one of the promising and economical methodology for the repair and rehabilitation of concrete structures. FRP sheets and strips provide lighter, easier to assemble, and more durable repair systems. Several field applications of externally bonded FRP reinforcement were executed in Japan [Nanni 1995], Europe [Meier et al. 1993], Canada [Alexander and Roger Cheng 1996], and the United States [Seible 1996]. In addition, several researchers [Meier 1993, Chajes et al. 1995, Saadatmanesh and Ehsani 1991, An et al., to name a few] have studied the behavior of concrete members strengthened with epoxy bonded FRP sheets or strips. Retrofitting of structures may be attributed to one or a combination of the following reasons: aging of structural elements, demand for increasing the service load, enhancing the structure performance under certain load conditions (e.g. seismic load), or complying to new building code requirements.

This paper presents a field application for strengthening of a roof structure using carbon fibre reinforced polymer (CFRP) strips for North End Water Pollution Control Centre, Winnipeg, Manitoba, Canada. Changing industrial demand at this plant necessitated strengthening of this sixty year old concrete precast roof structure. CFRP strips were selected due to their characteristics of high strength, low weight, ease of application, and non-alkali sensitivity to concrete. This technique introduced considerable savings in comparison to conventional repair methods proposed for the same structure.

GENERAL DESCRIPTION

Winnipeg North End Water Pollution Control Centre was built in early 1930s. No information on the roof system capacity could be located. It was assumed that the roof structure of this building was designed to carry its own weight, and snow load, in addition to a live load specified by the canadian code at this time for inaccessible roofs. The roof structure consists of fifty-six simply supported precast concrete panels of 2400 mm span and 450 mm width. Dimensions and reinforcement of a typical panel are shown in Fig. 1. Recent upgrading of the building demanded the installation of large equipment on the top of the existing roof creating significant drift snow load. To avoid costly replacement of the roof, it was decided to strengthen the existing roof to carry the additional loads using CFRP strips as illustrated in Fig. 1.

STRENGTHENING TECHNIQUE

The CFRP strips used in this project were the heavy-duty Sika® CarboDur strips bonded to the concrete surface by Sikadur-30 adhesive. This method was proven to be superior to the traditional methods [Emmons 1993], including external post-tensioning, section enlargement, and epoxy bonding of steel plates. Table 1 summarizes the advantages of the CarboDur strengthening system in comparison to epoxy bonding of steel plates commonly used for strengthening of similar structures. The application process of the CFRP strips requires minimum effort and does not interrupt the use of the building during construction. The construction time of the entire roof was four days.

The material characteristics of the CFRP strips, used in this project, are summarized in Table 2. The stress-strain profile of a CFRP strip is perfectly linearly elastic up to failure. The Sikadur-30 epoxy used for bonding the CFRP strips to the concrete surface is a solvent-free, thixtropic, epoxy-based two-component adhesive mortar. Two compounds A and B, are mixed together with a ratio of 3:1 to form the epoxy mortar. The epoxy mortar takes twenty-four hours to achieve its full strength.

TEST PROGRAM

An experimental program was conducted at the Structural Engineering and Construction R&D Facility at University of Manitoba, prior to construction. Selective panels were removed from the existing roof and brought into the structural laboratory, where they were subsequently strengthened with Sika CFRP strips and tested up to failure. This program intended to examine the behavior, including the load carrying capacities, for the existing panel before and after strengthening using Sika CFRP strips.

Preparation of Test Specimens

Control panel: A typical unstrengthened panel was tested up to failure with no preparation. ***Strengthened panels:*** Two panels were placed overhead in order to apply the CFRP strips to each rib of the panel under conditions similar to those on site, as described in the following section.

Test Setup and Instrumentation

The panels, with spans of 2.4 m, were tested as one way slabs supported by stiff cross beams, as shown in Fig. 2. The panels were tested using two static concentrated loads placed 0.80 m apart. A closed-loop MTS 1000-kN cyclic load testing machine was used to apply the load under stroke control. The strains in the top and bottom surfaces of the panel were monitored during testing using special displacement transducers (PI-gauges produced by Tokyo Sokki, Japan) over a certain gage length. The strains in the CFRP strips were measured using ten electrical strain gauges at different locations as shown in Fig. 3. To examine the bond between the concrete surface and the CFRP strip, and to monitor any slip, demec stations were glued onto the end of the CFRP strip and onto the concrete surface, as shown in Fig. 3. In addition, the deflection at the midspan was monitored on both sides of the panel by two linear variable differential transducers (LVDTs). A DATASCAN 7000 data acquisition system was used to transform the electrical signal from the LVDTs, the PI gauges, and the strain gauges into ASCII formated files.

TEST RESULTS

The tested panels were subjected to two concentrated loads, as shown in Fig. 2. Since the panels had been in service for a long period of time prior to testing, the panels were uniformly cracked along their length before testing began.

The control panel exhibited linear behavior up to yielding of the reinforcing bars, as can be determined from the load-deflection diagram (Fig. 4). Further loading, which was controlled by the stroke of the loading machine, caused the panel to deform excessively with no increase in the applied load. The failure of the control panel was mainly compression failure of the top flange.

The tested strengthened panels exhibited linear behavior up to failure, as shown in Fig. 4. Significant increase in the stiffness of the strengthened panels was observed in comparison to the control panel. It was observed that the mode of failure for the strengthened panels was changed from the ductile flexural failure to shear failure, with an increase in the load carrying capacity of about 10%.

The load vs. midspan deflection and concrete strains for the unstrengthened control panel and a typical strengthened panel are shown in Figs. 4 and 5. The panels strengthened by CFRP strips showed significant gain in the overall stiffness. The increase in the load carrying capacity, compared with the control panel, was not significant as the failure mode for the strengthened panel changed from the ductile flexural failure to shear failure.

The strain distribution along the CFRP strip from midspan to support is shown in Fig. 6 at various load levels. As can be seen in Fig. 6, the strain distribution in the CFRP strip increases uniformly as the load increases, indicating that perfect bond between the CFRP strip and concrete surface up to failure. The same conclusion was also drawn from the dial gauge readings of the demec stations at the end of the CFRP strips.

ANALYTICAL MODEL

Behavior of the panels were analyzed using two different methods. In the first method, the deflection was calculated based on integration of the curvature along the span of the panel. The curvature was calculated as the slope of the strain profile which was determined using the strain compatibility approach as shown in Fig. 7. A quadratic relationship, given in eq.[1] was used to model the stress-strain relationship of the concrete in compression.

[1] $$f_c = f_c'\left[\frac{2\varepsilon_c}{\varepsilon_{co}} - \left(\frac{\varepsilon_c}{\varepsilon_{co}}\right)^2\right]; \varepsilon_c \le \varepsilon_{c\max}$$

where, ε_{co} is the concrete strain corresponding to f_c'(=0.002), and ε_{cmax} is the maximum concrete strain (=0.003). The compression strength of concrete f_c' was determined using a Schemidt hammer test and found to be 41 MPa. The rupture modulus of the concrete f_r, was neglected in this analysis since the roof panels were uniformly cracked before the testing. Elasto-plastic behavior was assumed for the steel reinforcement with a yield strength of 520 MPa, as measured by uniaxial tension tests. The FRP material was assumed to be linear elastic, up to failure based on the material characteristics given in Table 1. This analytical method allows flexural failure of beams to occur either by crushing of concrete or rupture of the FRP strips. In both cases, yielding of internal reinforcing bars occurred before failure. The shear capacity of the panels was determined according to ACI318-95 (eq. 11-3).

In the second method, the deflection was calculated according to the ACI318-95 code, using eq.[2]

[2] $$\Delta = \frac{23\,M\,l^2}{216\,E_c\,I_e}$$

where, M is the moment in the constant moment zone, l is the span of the panel and I_e is the effective moment of inertia which was assumed to be the cracked moment of inertia I_{cr} of the transformed section, given in eq.[3].

[3] $$I_e = I_{cr} = (Bc^3)/3 + n_s A_s (d_s - c)^2 + n_f A_f (d_f - c)^2$$

where, $n_s = E_s/E_c$, $n_f = E_{frp}/E_c$, and c is the depth of the compression zone, which can be determined using eq. [4].

[4] $$c = \sqrt{\frac{(n_s A_s + n_f A_f)^2}{B^2} + \frac{2(n_s A_s d_s + n_f A_f d_f)}{B}} - \frac{(n_s A_s + n_f A_f)}{B}, \quad c \le t_s$$

The predicted load deflection, using the two methods, for the unstrengthened and strengthened panels were very close to the measured load deflection for the tested panels, as shown in Fig. 4. Predicted ultimate loads, based on the shear capacity of the panels, were less than measured loads by 10 and 20 percent for the control and strengthened panels, respectively, as shown in Fig. 4. Predicted FRP strains were close to measured strains (Fig. 5 and Fig. 8) while predicted concrete strains at the top fiber of the compression zone were less than measured strain by 35 percent.

CONCLUSION

A control panel and strengthened panels were tested to evaluate the behavior of concrete panels with CFRP strips. Theoretical models were proposed to predict the behavior of the strengthened panels. The findings of this investigation can be summarized as follows:

1. This project confirms the efficiency and economical advantages of using CFRP for strengthening and retrofitting existing structures.
2. The strengthened panels behaved linearly up to failure, showing an increase in the stiffness. The gain in stiffness minimized the deformation and subsequently controlled the cracks under service load level.
3. The CFRP strips were perfectly bonded to the concrete surface. This perfect bond was achieved by using the two compound sikadur-30 adhesive epoxy.
4. Behavior of the stengthened panels could be accurately predicted by integration of the curvature along the panel length. The simplified I_e method, adopted by ACI318-95 code is adequate for design purposes prior to yielding of the steel reinforcement and by considering no tension resistance for the old concrete.

5. Shear capacity of all of the tested panels exceeded the predicted values by the ACI318-95.

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Table 1 - Comparison between CFRP Strips and Steel Plates Strengthening Systems

Criteria	Strengthening with CFRP strips	Strengthening with steel plates
Own weight	Low	High
Tensile strength	Very high	High
Overall thickness	Very thin	Small
Corrosion	None	Yes
Length of strips	Any	Limited
Handling	Flexible, easy	Difficult, rigid
Load bearing	In the direction of the fibres only	In any direction
Laps	Easy	Complex
Fatigue behavior	Outstanding	Adequate
Material costs	High	Low
Installation costs	Low	High
Application	No tools	require lifting equipment and clamping device

Table 2 - Characteristics of CFRP Strips

Material	Continuous carbon fibers in polymeric resin
Fiber volumetric content	60%
Dimensions	50 mm width 1.2 mm thickness
specific gravity	1.6
guaranteed tensile strength	2400 MPa
Elastic Modulus	150,000 MPa
Strain at failure	1.4 %
Stress-strain profile	linear up to rupture

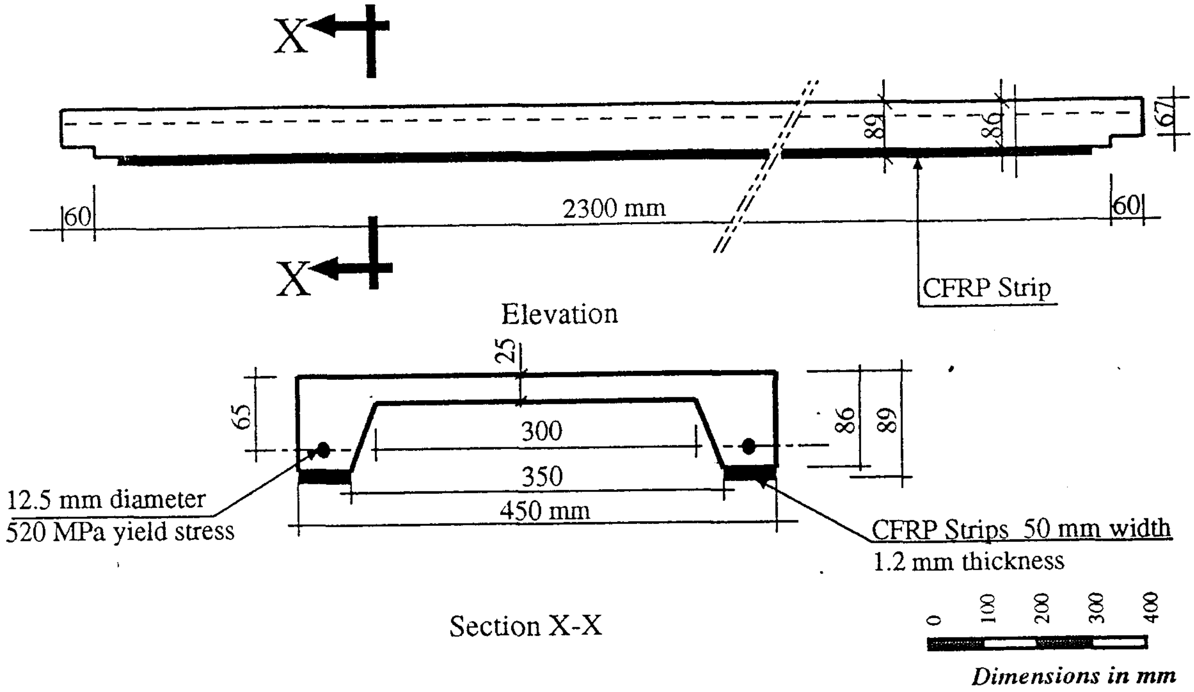

Fig. 1 Dimensions and reinforcement of a typical panel

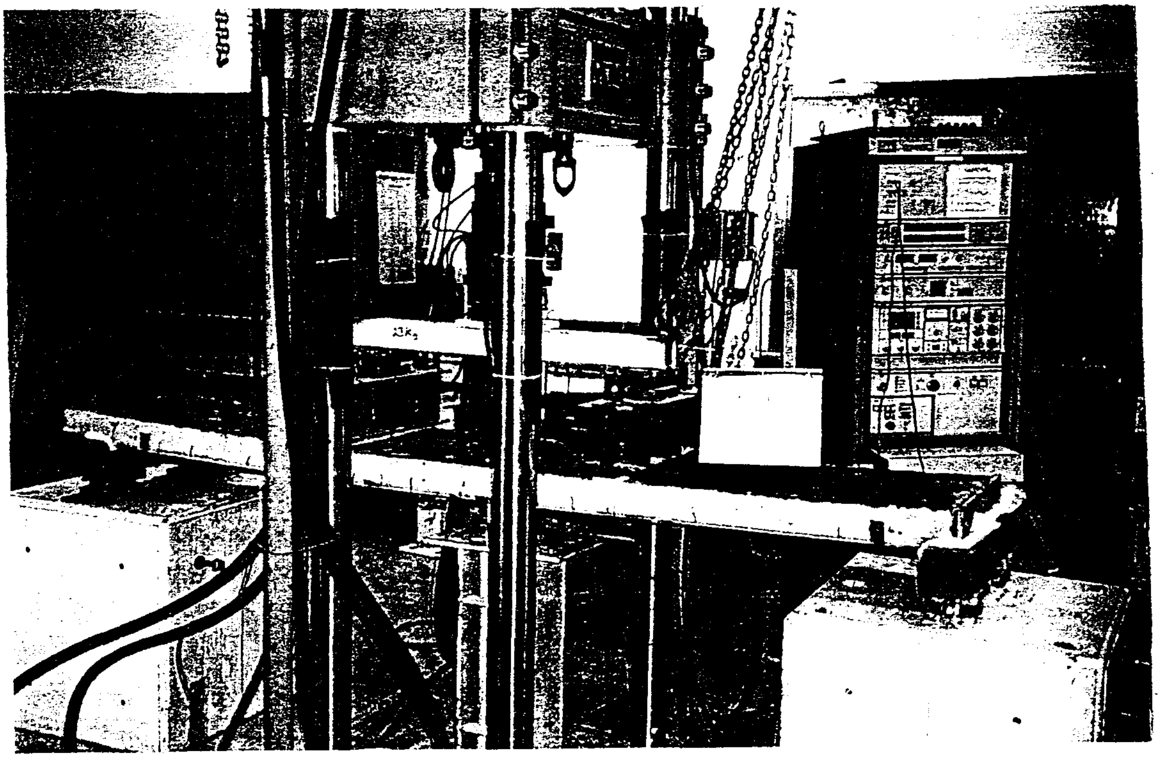

Fig. 2 Test setup at University of Manitoba

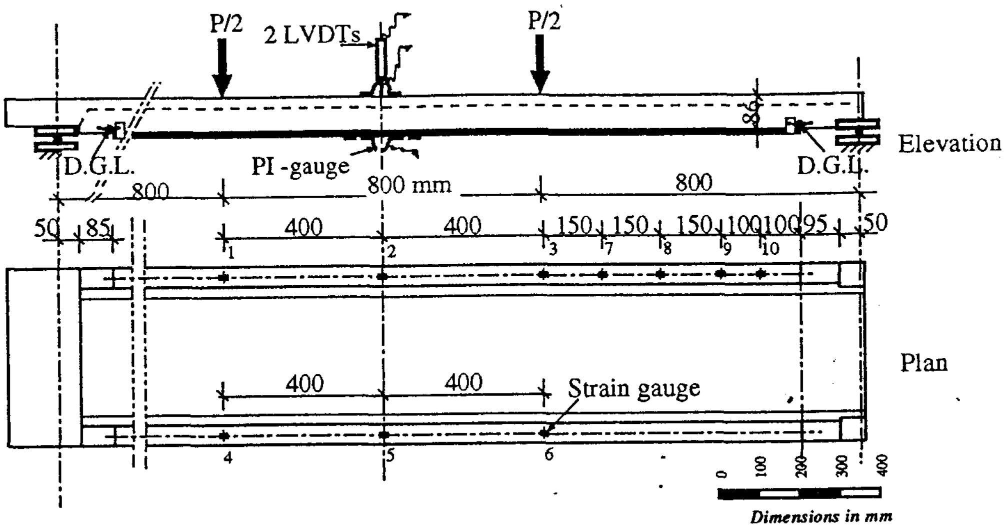

Fig. 3 Instrumentation on Typical Strengthened Panel

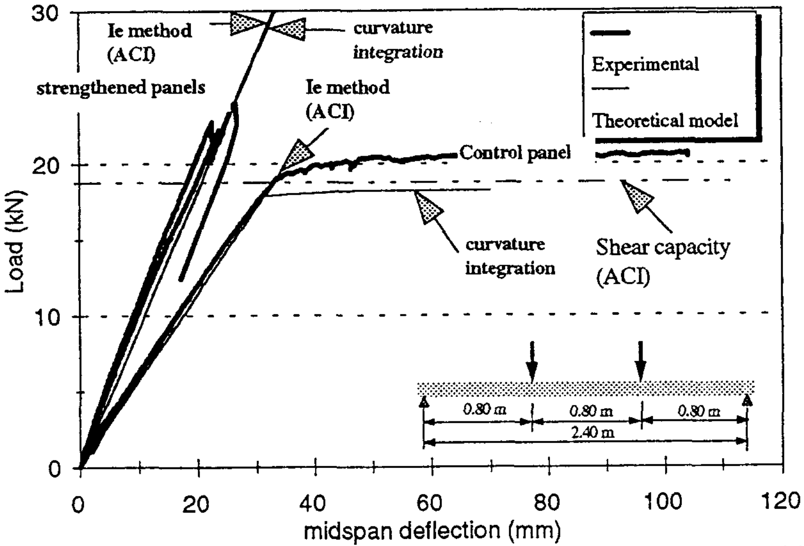

Fig. 4 Load-Deflection Diagrams : Control Panel & Strengthened Panels

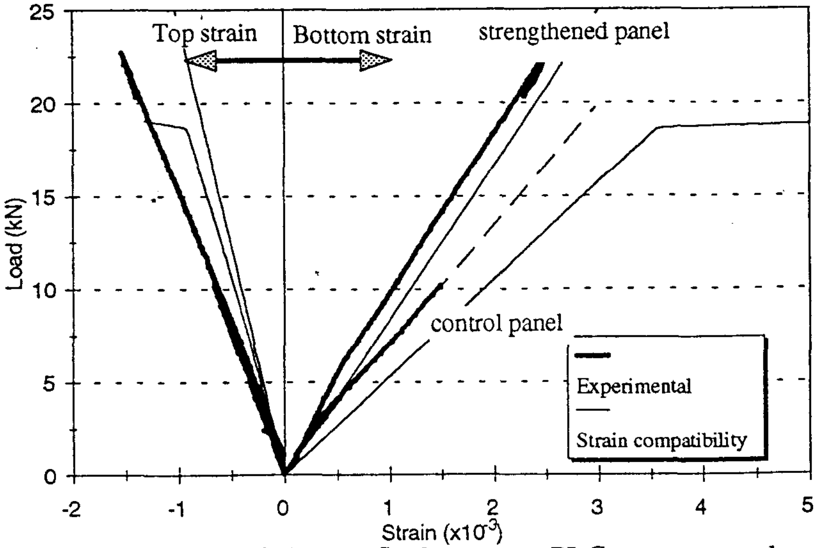

Fig. 5 Strains at Top & Bottom Surfaces using PI-Gauges : control panel and Strengthened Panels

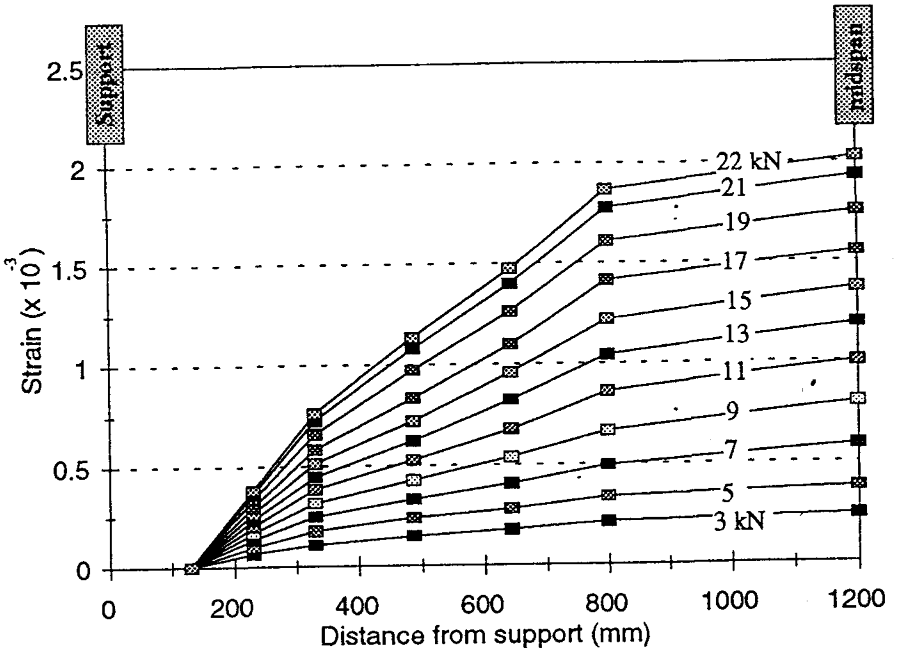

Fig. 6 Strain Distribution Along CFRP strip : Strengthened Panel

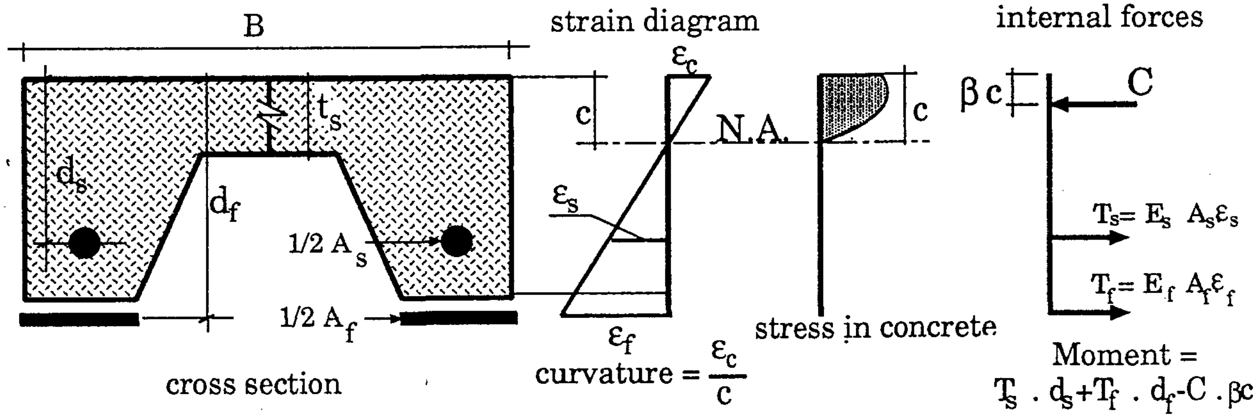

Fig.7 Stress distribution within the cross section

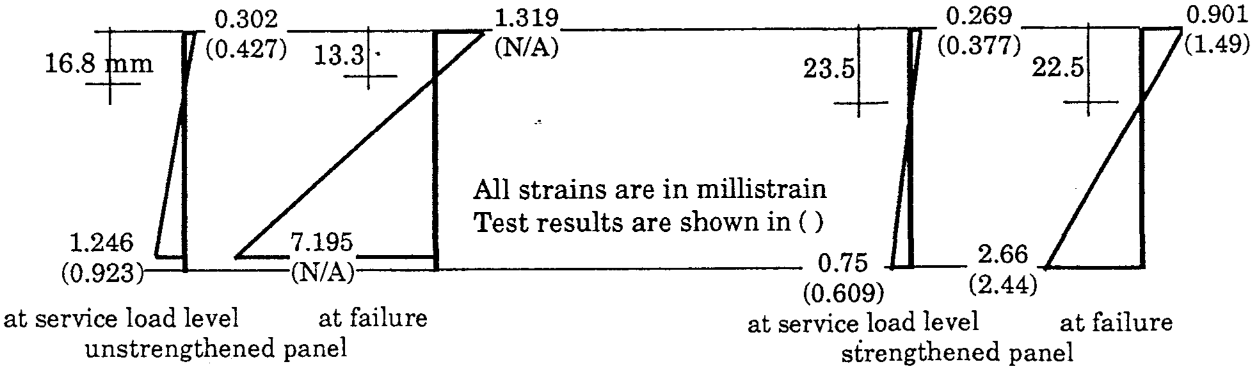

Fig.8 Predicted strain profiles at service load level and at failure