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Paper No. 1740. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

SEISMIC BEHAVIOUR OF LACED REINFORCED CONCRETE BEAMS

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ABSTRACT

This paper describes the ductility behaviour of Laced Reinforced Concrete (LRC) beams. LRC beams and panels are widely used in blast resistant design of structures. Lacing is a form of continuous shear reinforcement as compared to the form of conventional stirrup reinforcement. It is placed in the plane of principal bending and anchored in position by means of transverse bars. In general ductile failure of RC beams with conventional stirrups is not possible when the shear span-to-depth ratio is less than 2.5 due to the influence of severe diagonal cracking. Improved ductile failure of such members can be achieved by proper detailing of reinforcement with inclined bars in the case of normal concrete mix, and also by improving the tensile strength and ultimate strain of concrete with the help of steel fibres. Hence, the experimental programme includes various forms of lacing such as inclined tied lacing, inclined welded lacing, rectangle lacing and single leg lacing using normal and fibre reinforced concrete. About 20 LRC specimens were tested under monotonic and cyclic loading. A typical cyclic displacement controlled loading in proportion of the yield displacement was imposed on the test beams by servo-controlled electro-hydraulic actuator. The plastic hinge zone was instrumented to obtain the flexure and shear response using the on-line data acquisition system. A new damage model accounting static and cyclic ductility indices has been proposed based on the experimental data. Test results indicate that LRC beams even with large tension steel can effectively eliminate brittle failure thus ensuring large ductility and sustained resistance over large yield plateau. With optimum use of fibre and inclined lacing, precast high ductile joints can be used in practice.

KEYWORDS

Inclined bars; static; cyclic shear; blast; damage index; ductility; hinges; steel fibres; beams; precast elements

INTRODUCTION

Very often reinforced concrete structures are to be designed for severe dynamic loads such as earthquake or blast loads. As these loads are very high in magnitude and last only for small interval of time, several codes of practice impose the criteria of ductile failure apart from strength and stability criteria. In the last two decades considerable attention has been focused to achieve higher ductility levels by the appropriate choice of proper cement concrete matrix with the combination of steel fibres and detailing of reinforcement. The principal targets to be achieved for a ductile structure are 1) adequate resistance 2) large inelastic deformation with sustained resistance and 3) no local or premature failure of subassemblies. Special attention is to be given to know the collapse mechanism of sub-assemblies such as columns, beams, beam-column junctions under the influence of predominant shear or flexure, or shear and flexure. This paper considers the ductility behaviour of LRC beams having shear span-to-depth ratio of 2.6, which are governed by predominant shear loading.

Laced construction is popular in steel industrial structures for purlins, columns and beams. Similarly the use of inclined reinforcement as special reinforcement in reinforced concrete structures particularly in spandrel beams and short columns are commonly used in practice. So far the application of laced reinforced concrete has been limited to blast resistant structures. Lacing is provided in linear or plane elements by taking the continuous inclined reinforcement (lacing) around the transverse reinforced bars. Depending on the magnitude of shear force lacing can be provided in one or more planes. Generally doubly reinforced sections with symmetric lacing can be used considering the reversal loading under dynamic action. The types of lacing are 1) inclined - preferable inclination with respect to principal reinforcement is between 40^0 and 60^0 (see figure 1), 2) rectangle - 90^0 inclination and very easy in placing the lacing as compared to the inclined form, and 3) single leg lacing which has only one leg and is discontinuous in form. Tack welding of inclined lacing has been considered as a suggestive step for precast construction to ease the construction practice. A combination of inclined and conventional stirrup arrangement has also been considered as another variable in this study.

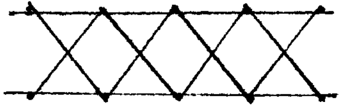
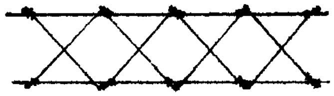
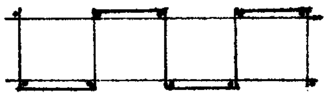
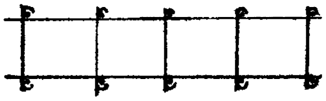
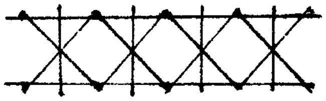
BRIEF REVIEW OF PAST INVESTIGATIONS

The application of laced reinforcement was confined to blast resistant design of structures. The exhaustive manual (TM 5-1300, 1984) details the advantages of LRC elements such as - 1) large support rotation that can be obtained as compared to conventional stirrup reinforced elements, 2) typical strain hardening beyond yield plateau under inelastic deformation, 3) limited spalling after yield limit and 4) high shear resistance under transient blast loading. Further investigations carriedout by Kiger et al., (1989) and Lakshmanan et al., (1991) indicate the superior performance of LRC elements in inelastic region under blast loads, except for high cost of construction as compared to the usual stirrup construction methods. Paulay (1971) introduced the concept of diagonal arrangement of main reinforcements to prevent concrete spandrel beams from brittle failure under shear. The investigations on beams and short concrete columns conducted by Bertero (1973) and Minami et al., (1980) have revealed that shear failures under high cyclic shear are undesirable. With the advent of diagonal arrangement of reinforcement the advantages were found to be 1) no appreciable deterioration after the attainment of the maximum capacity and 2) stable hysteresis loops with large capacity of energy dissipation. Tagos et al., (1988) have conducted experimental studies on low slender structural elements having shear span-to-depth ratio varying between 1.0 and 2.0. The plastic rotations obtained using rhombic reinforcements were compared to be large with conventional reinforced specimens under combined flexure and shear influence. Thus it shows that inclined reinforcement is found to be one of the most effective ways to improve the seismic resistance of reinforced short columns and beams, specially under predominant shear influence.

EXPERIMENTAL STUDIES ON LRC BEAMS

The experimental programme consists of evaluation of various lacing forms while keeping the longitudinal reinforcement and cross section of beam as the same. The spacings of nodes in lacing were kept constant at 160mm. The cantilever beam with the cross section of 300 x 300 mm and height of 0.82m was selected and detailed sufficiently for fixity at the base (see figure 1). The shear span-to-depth ratio of various test beams was fixed at 2.6. The monotonic and cyclic loads were applied at a distance of 0.66m from the base of cantilever. The test specimens were anchored to the test floor through rigid steel girders. Actuator was connected to the test specimen with a swivel end and connecting plates. All the test beams were cast as per DIN 1045 specifications using BI grade or strength class B25 concrete. High tensile weldable quality steel BSt 500/550 S was used for all reinforcing bars. All the lacing and longitudinal bars were 12mm diameter. Eight special large strain-displacement gages were used to obtain curvature and shear strains at the hinge location. The details of the experimental programme are given in table 1.

Table 1. Details of experimental programme

Mix & No. of beams	Beam code	Lacing form & construction method	Schematic figure of shear reinforcement form	Tests
RC10 - 3	TL	Inclined -tied		Static + cyclic
SFRC10 - 3	STL			
RC10 - 3	WL	Inclined-welded		Static + cyclic
SFRC10 - 3	SWL			
RC10 - 3	RL	Rectangle-tied		Static + cyclic
SFRC10 - 3	SRL			
RC10 - 1	SL	Singleleg-tied		Static
SFRC10 - 1	SSL			
RC3 - 2	CTL	Conventional+TL		Static + cyclic
RC3 - 1	CWL	Conventional+WL		Cyclic

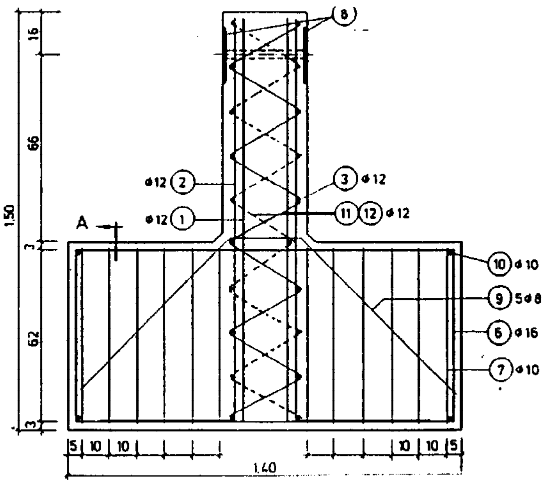


Fig. 1 Laced reinforced concrete cantilever test beam.

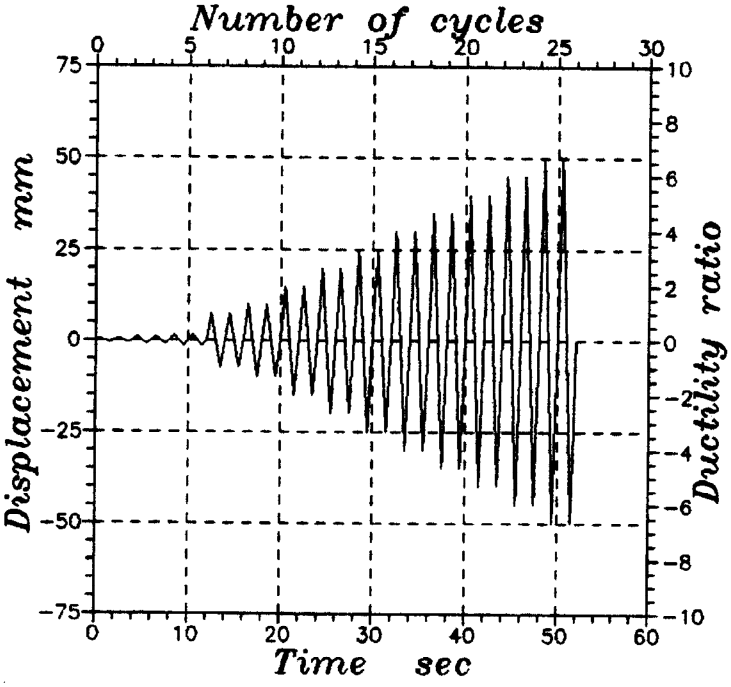


Fig. 2 Imposed cyclic displacement history.

During the monotonic tests, the static load was applied at the rate of 1mm/sec and the maximum displacement was limited to 120mm. The cyclic displacement controlled loading was designed based on the three distinct levels of RC specimen behaviour. They were tensile cracking limit, yield limit, and post yield range. In the post yield stage the displacement increment was approximately controlled in steps of half of the yield displacement upto the failure of the specimen. Two equal displacement level cycles were applied at each displacement level till the failure of the specimen took place (see figure 2). For all the specimens the cyclic displacement was maintained constant for better comparison.

DUCTILITY EVALUATION

Yield deformation of a member depends on the type of reinforcement (mild steel or high strength deformed bars), diameter of the bars and position with in the cross section. Similarly the ultimate deformation depends on the criteria of failure. The yield and ultimate deformation defined by various investigators vary as there is no unified procedure is available. The procedure suggested by Park (1991) and Sheikh et al (1993) are similar and is used in this work to evaluate various test beams. The yield deformation of the equivalent elasto-plastic system has been considered corresponding to the deformation at 75% of the peak lateral load. The displacement corresponding to rupture of tension steel or that corresponding to 85% of peak load (beyond the yield stage) is considered as the ultimate deformation. This approach gives conservative ductility indices for the evaluation of reinforced concrete structural components. It ensures sufficient yielding of majority of tension steel at the yield point and acceptable load sustaining capacity at the point of ultimate deformation. The typical load-deformation plots of the test beams using normal concrete is shown in figure 3. The displacement and curvature ductilities obtained for various test beams is given in table 2. It can be concluded that inclined lacing with and without steel fibres provide better response as compared to the other forms of lacing. The typical hysteritic plot of load and deformation obtained from test beam is shown in figure 4.

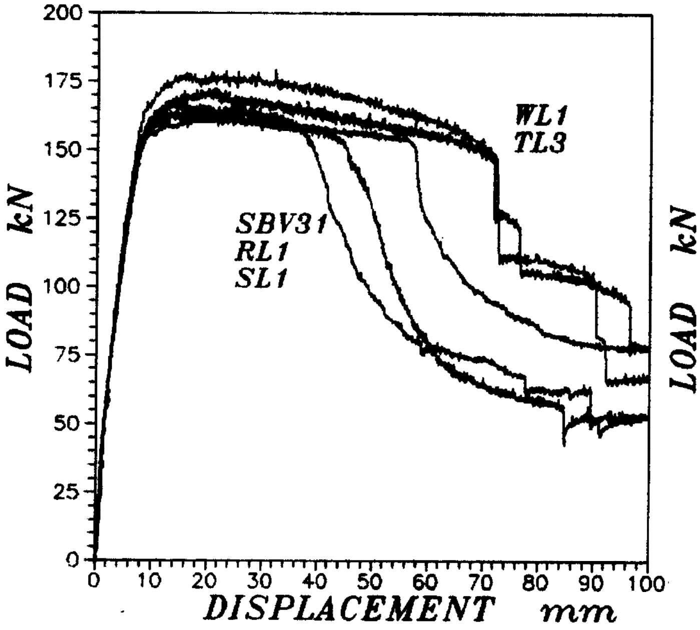


Fig. 3 Monotonic load-displacement plots of LRC beams.

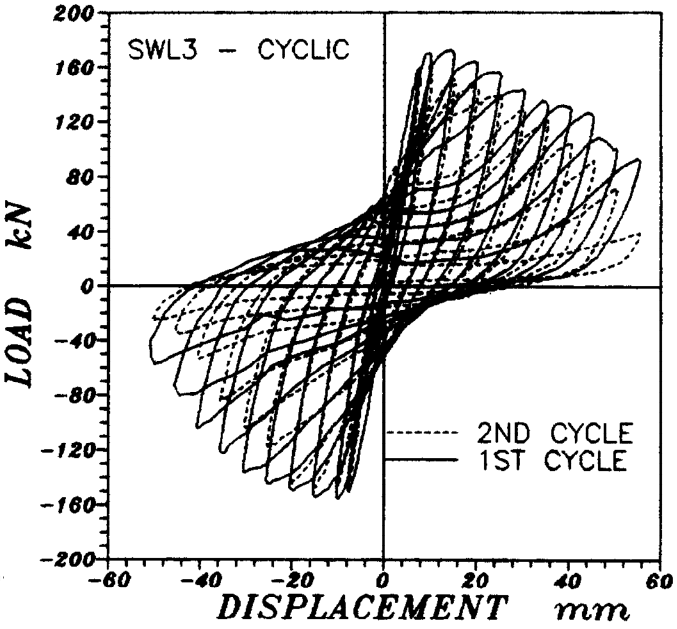


Fig. 4 Cyclic load-displacement plot of LRC beam.

The hysteresis loops are well stabilised particularly for inclined laced members and it is more so for steel fibre reinforced concrete members. Here it can be noticed that strength and stiffness deterioration of about 15% is consistent during each secondary repeating cycle which follows after the primary cycle of the same displacement amplitude. Earlier investigations carriedout have shown that there is negligible drop in load if more than two cycles of load are applied at one deformation stage (Gonzalez et al., 1990). This trend continues even beyond the maximum deformation (corresponding to 15% load drop). Hence, it is possible to relate the damage index interms of two successive repeated cycles and ductility values obtained from the above procedure.

Table 2. Ductility values of test beams

Series	Concrete mix	Compressive strength N/mm^2	Static ductility μ_{cy}	Cyclic ductility μ_{st}	Static failure
RL	RC10	40.6	3.0	6.0	shear
TL	RC10	40.6	3.5	9.0	flexural tension
WL	RC10	40.6	3.6	9.0	flexural tension
CTL	RC3	29.8	3.1	9.8	flexural compression
SRL	SFRC10	29.8	3.4	9.6	flexural tension
STL	SFRC10	29.8	3.6	10.2	flexural tension
SWL	SFRC10	29.8	3.9	9.5	flexural tension

DAMAGE INDEX

The damage index is useful in earthquake resistant design of structures to assess the reserve strength available in the member after experiencing the quasi-static cyclic loading. Park and Ang (1985) developed a linear relation in terms of displacement ratio and absorbed cyclic energy as follows -

$$D = \frac{\Delta_m}{\Delta_u} + \frac{\beta}{Q_y \Delta_u} \int dE, \qquad (1)$$

where Δ_m and Δ_u are the deformations corresponding to earthquake and monotonic loadings respectively. Q_y, dE, and β are the yield strength, incremental absorbed hysteritic energy and parameter to account cyclic load effect respectively. An empirical equation has been suggested to define the value of β. It does not account the imposed displacement history on the component. Hence it is considered to evaluate β based on the ductility indices and the number of cyclic excursions in a quasi-static test programme. Based on the experimental observations, the simplified damage model developed is as follows -

$$D = \frac{\mu_{cy}}{\mu_{st}} + \beta \frac{\sum E_{cy-\Delta}}{\sum 2E_{st-\Delta}} \qquad (2)$$

This equation is similar to equation 1. But it has been modified to account the known design variables such as cyclic (μ_{cy}) and monotonic (μ_{st}) ductility indices. The energy term has also been modified to account the true cyclic cumulative and monotonic energy dissipation at a given displacement, (Δ). The factor 2 in the denominator accounts symmetric energy dissipation under positive and negative loading of monotonic loading. In the case of unsymmetric reinforcement of longitudinal steel, this factor can be varied between 1 and 2 based on the strengths in the respective directions. The value of β has been fixed at the intersection point of two particular cases namely, a) considering 2 symmetrical cycles at every cyclic displacement and b) considering cumulative effect of all cycles upto the displacement level under consideration. In all the cases β values are derived for the maximum damage index, D equals to 100%. A typical plot of β with first term in equation 2 is shown in figure 5. The average β obtained for all the test specimens are found to be 1.25 with a variation of 7%.

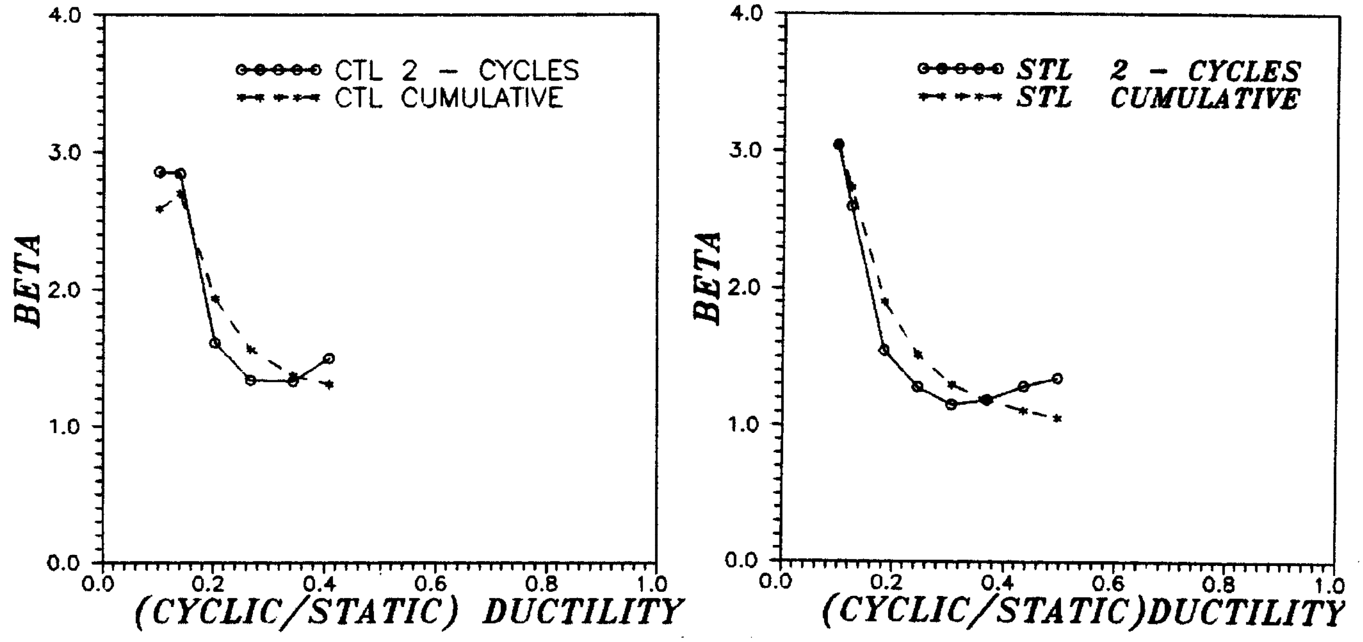


Fig. 5 Determination of energy dissipation constant to predict damage index from quasi-static tests.

From the experimental results the cyclic and static ductility indices can be related as follows -

$$\mu_{cy} = 0.4 * \mu_{st} \cdot \tag{3}$$

For any level of required cyclic ductility, $\mu_{dy,}$ the damage index can be computed using equation (4) is as follows

$$D = \left(\frac{\mu_{dy}}{\mu_{st}}\right) + \beta\left(\frac{\mu_{dy}}{\mu_{cy}}\right)\left(\frac{\Sigma E_{cy-\Delta}}{\Sigma 2E_{st-\Delta}}\right) \tag{4}$$

The computed damage at yield point in the present experimental programme is 49%. So the damage index of about 51% is spread between yield point and maximum deformation

EVALUATION OF MONOTONIC TEST RESULTS

M-Φ_{avg}analysis

The longitudinal strains in concrete and steel at various levels are assumed to be directly proportional to the distances from the neutral axis based on the assumption that plane sections remain plane . It is possible to define the total strain distribution in the composite by means of the extreme fibre strain and curvature $\Phi_{avg.}$ Four layers of reinforcement at a critical section of the doubly reinforced beam have been considered to obtain the true longitudinal strain distribution. For a known compression strain of concrete, the neutral axis depth is determined by the iterative analysis till the equilibrium condition is satisfied. Stress-strain relationship for the concrete under compression has been considered using the Kent and Park (1971) model. The typical results of M-Φ_{avg} of analytical and experimental results obtained are shown in figure 6. All the beams with inclined lacing failed by rupture of tension steel. The single leg and rectangle lacing beams were failed under predominant shear. Thus it shows that when the diagonal compression and tension chords are adequately reinforced, the ultimate failure occurs by rupture of tension steel leading enormous increase in failure ductility and energy absorption, which is advantageous in earthquake resistant design of structures and structural components.

Q-γ_{avg} analysis

Based on the on-line data from large displacement gages shear displacement, γ_{avg} has been computed. Theoretical formulations have been developed based on Vechio and Collins (1987) approach. All the test beams with various types of web reinforcement have been analyzed and the typical results are shown in figure 7.

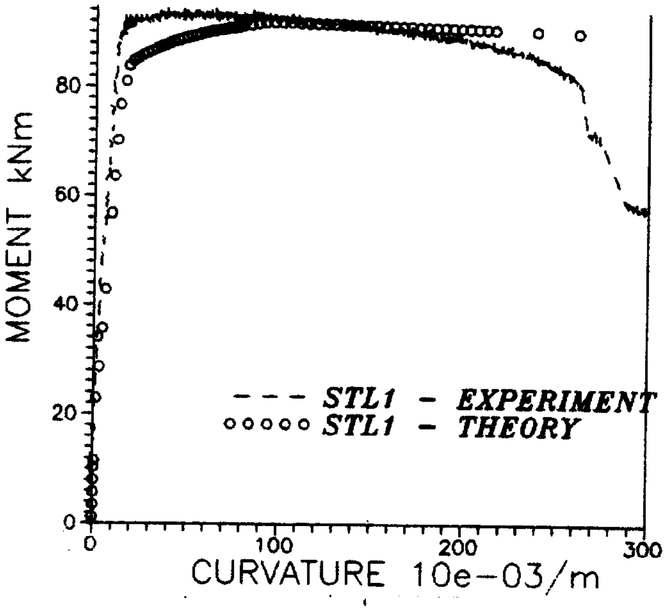


Fig. 6 Flexure response of LRC beams.

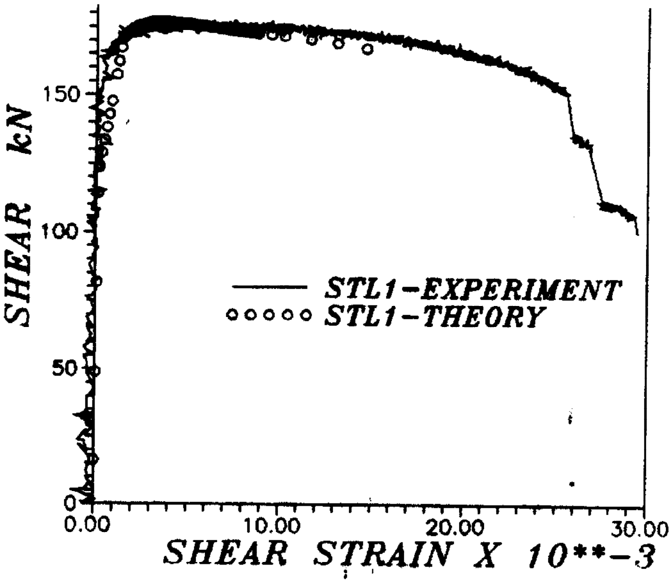


Fig. 7 Shear response of LRC beams.

This procedure predicts accurate results of shear-deformation response for no stirrup case and short shear span members which are governed by shear. But for tension steel yield cases under flexure and shear, limiting the shear force corresponding to tension steel yield state is essential.

CONCLUSIONS

Lacings can be effectively used to obtain ductile failure even under the influence of high cyclic shear. In order to overcome the cost of fabrication prefabrication measures such as tack welding of lacing is also found to effective for practical use. Arrangement of inclined lacing can be only in the direction of predominant shear and in a plane perpendicular to the major axis bending. A combination of conventional and lacing shear reinforcement can also be used at the plastic hinge locations, for additional confinement at cross section.

ACKNOWLEDGMENTS

The second and third author gratefully acknowledge the kind support received from Director, Structural Engineering Research Center, Madras, India. The kind support received from German Academic Exchange Service (DAAD), Bonn, Germany is gratefully acknowledged.

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