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Experimental study of slab-wall connections

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ABSTRACT

This paper presents results of an experimental study on seismic behaviour of interior slab to wall connections. In the study, a half-scale model of a typical slab-wall connection was tested under the combination of cyclic lateral loads and distributed vertical loads (which simulated service gravity loads of the slabs in the full-scale prototype). Test results indicated that the connection between the slab and the wall experienced severe damage at early stages of the test, a result likely to influence the internal force distribution patterns occurring in indeterminate structures under lateral loads. Damage was accentuated by the presence of gravity load, and was manifested by the formation of shear sliding planes in the slabs.

INTRODUCTION

The study presented herein was motivated by the current design requirements for slab-wall and frame-wall structures which primarily consider the base of the walls as the critical sections for lateral load design. This practice reflects the assumption that the lateral loads are mainly resisted by the stiffer vertical elements of the structure, i.e. the shear-walls. In reality, the base-shear capacity of a structural wall can only be mobilized if the horizontal diaphragms of the structure are sufficiently stiff in their plane, so that lateral forces are distributed to the vertical elements (columns and walls) according to their lateral stiffness. In most reinforced concrete frame-wall structures, a large portion of the total mass is accumulated at the floor slabs of the structure; therefore, accelerations induced by earthquakes are likely to cause the development of large inertia forces in the slabs. If for the imposed lateral displacement levels the slab-wall connection possesses insufficient stiffness and strength, it is likely that horizontal forces will be diverted to the other vertical elements of the structure (e.g. columns); in such case, lateral forces will not be resisted by the wall, even if the wall possesses the desired strength, and therefore it is conceivable that in such circumstances it may not be possible to maintain the

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desirable hierarchy of failure in the structure.

Behaviour of the slab-wall connections is characterized by two features:
1) When horizontal diaphragms are flexible in their planes, the mechanism of in-plane shear transfer occurring between floor slabs and walls is governed by deep beam action developing in the slabs. Because of the deep beam action, a portion of the vertical interface between slab and walls is under normal tension, and is therefore expected to crack under moderate levels of lateral drift. Cracking is likely to cause redistribution of in-plane shear stresses in the flexural compression zone (Fig. 1).
2) The gravity loads which are inevitably present in the slab, induce negative moments at the supports. Associated with the normal tension which results from the flexural action of the moments are the following effects: a) the available preyielding range of the longitudinal slab reinforcement is reduced, and b) vertical flexural cracks which form at the connection, reduce the area of contact between slab and wall, over which shear transfer can take place.

The objective of this paper is to present the results of an experimental study of the lateral load behaviour of a slab-wall connection. The study focused on the characteristics of the deep beam action and gravity load effects summarized in the preceding. In the experimental program, a half scale model of a typical connection was tested under various levels of loading up to failure in order to obtain the load-deformation characteristics of the model and to identify its failure mechanisms.

EXPERIMENTAL PROGRAM

A series of experiments investigating the behaviour of slab-wall connections which had been previously carried out by Nakashima et al. (1981), (1982), had shown that in cases of strong walls and flexible slabs, failure occurring in the slab close to the connection can be the mechanism which controls the pattern of lateral load distribution through the structure. In these specimens longitudinal slab reinforcement was designed according to the standard practice, and was therefore cut-off at the location where moments associated with gravity loads vanished. However, during testing it was concluded that in-plane shear and bending moments which developed under the action of lateral loads were significant in that region. As a result, the section along the boundary where the longitudinal slab reinforcement was cut-off, was a weak region for in-plane shear transfer, and eventually controlled the failure of the specimen.

Because of the formation of a full-depth sliding plane at the location where reinforcement was cut-off in Nakashima's tests (1981), and contrary to common practice, top and bottom reinforcement was continuous over the point of zero gravity moment in the slabs of the specimen tested at the University of Toronto. The specimen was a half-scale model of a typical interior slab-wall connection (Fig. 2), and was subjected to the lateral load history shown in Fig. 3. The loads were introduced at the ends of the slabs, in order to simulate development and transfer of inertia forces from the slab to the wall. Displacement levels corresponding to 0.25, 0.5, 0.75, 1., 1.5, 2. and 3 times the theoretical yield displacement of the specimen were subsequently applied. (Theoretical yield displacement for the specimen, computed including both flexural and shear deformations was 7 mm, from the tip of the slab to the base of the wall).

The design of the specimen followed the CSA Standard CAN3-A23.3-M84 (1984). The floor slab was reinforced with 8 mm diameter bars at 175 mm and 240 mm o.c. in the longitudinal direction (top and bottom respectively). In addition, a minimum of $0.002*A_{gross}$ was provided as transverse reinforcement in the slab (6 mm diameter bars at 250 mm top and bottom). During the test, the self weight and the added distributed weights over the slabs amounted to 5.8 Kpa, which is approximately the load required to produce the cracking flexural moment at the face of the interior support. The span of the floor slab in the specimen corresponded to the approximate location of inflection points resulting under the action of gravity loads. The shear wall was designed to develop a maximum shear stress not exceeding approximately $0.5\sqrt{f'_c}$ Mpa (for ductile failure). The wall contained 0.37% and 0.54% vertical and horizontal web reinforcement respectively (2 curtains consisting of 8 mm horizontal bars at 150 mm o.c., and 8 mm vertical bars at 220 mm o.c.). The boundary elements contained 2% of the gross area of the wall in vertical reinforcement. Details of the slab and wall reinforcement are presented elsewhere (Imran 1990).

Concrete used for fabrication of the specimen had a cylinder compressive strength of 32.5 Mpa, and splitting strength of 3 Mpa. Reinforcing bars had a nominal yield strength of 400 Mpa, but actual yielding for the 8 mm diameter bars occurred at 607 Mpa, whereas for the 10 mm diameter bars, at 465 Mpa. The respective ultimate strengths were 680 and 630 Mpa. In addition to LVDT's, and reinforcement strain gauges, Zurich targets were placed on all the faces of the specimen on a 200 mm grid, and the configurations of these targets were monitored throughout the test in order to obtain surface strains of concrete.

During the test, the floor-slabs were propped at their free ends by means of roller supports. The specimen was post-tensioned to the Laboratory strong floor in order to simulate full fixity at its base.

RESULTS

The floor slabs of the specimen experienced a sharp stiffness reduction even at small-amplitude cycles corresponding to displacement levels of $0.5\ \Delta_y$. The stiffness reduction was accompanied by formation of flexural-shear cracks in the slab, at the connection with wall; cracks forming in the upper part of the wall were continuation of the slab cracks in the vicinity of the connection (Fig. 4).

Full-depth major cracks, (resembling the sliding cracks which had been earlier reported by Nakashima (1982)), developed in the slabs parallel to the wall, but contrary to the reference tests these cracks did not control the failure mechanism of the specimen. The first crack was located at the face of the connection with the wall; the second was located at a distance of approximately a quarter of the span from the interior support. This point also corresponds to the approximate location of the inflection line, or point of zero gravity moments in the slab; it is therefore the location of a state of pure vertical shear, which acts in combination with the in-plane shears induced in the slab during the test. For this reason, the point of inflection in the slab is a potential weak link, which may control the in-plane shear resistance of the horizontal diaphragm if longitudinal reinforcement is cut-off (as seen in Nakashima's tests).

At large levels of lateral displacement, widening of flexural cracks was observed at the interface of the slab-wall connection. The growth of the slab in its plane in the direction of the load appeared to affect the pattern of cracks in the wall (Fig. 4), and it is believed that might have also affected the wall strength. The increasing elongation of the slab was also evident from the fact that the strain recorded on the transverse reinforcement remained in tension regardless the direction of loading (Fig. 5). Furthermore, because the specimen was statically determinate, expansion in the slab was unrestrained in both the longitudinal and the transverse directions. However, such an expansion is likely to be partially restrained by the adjacent slab panels in a continuous structure, therefore causing development of internal actions which would likely affect the internal force distribution throughout the structure. For this reason, further study to understand the effect of nonlinear slab deformations on the overall behavior of the structure is necessary.

The hysteretic load displacement relationship of the specimen is plotted in Fig. 6 (displacements were measured at the tip of the east slab panel relative to the support). Yielding of the slab and wall reinforcement occurred simultaneously at 0.36% total lateral drift. The respective relative contributions of slab and wall were, 0.13% of the slab length, (measured relative to the face of the connection) and 0.22% of the wall height, (measured relative to the base). At that displacement level, the average shear stresses developing at the vertical and horizontal faces of the connection were $0.19\sqrt{f'_c}$ and $0.3\sqrt{f'_c}$ respectively. The maximum total lateral displacement of the specimen attained during the test was 1.25% of the wall height; at that stage, the average in-plane shear stress in the slab was $0.25\sqrt{f'_c}$, while shear stresses in the wall reached $0.39\sqrt{f'_c}$. Previous tests (Nakashima 1981) also indicated similar or lower levels of average shear stress developing at the vertical face of the slab-wall connection. It is believed that this reduced level shear resistance of the slab side of the connection was primarily caused by the influence of gravity loads and by the lack of the beneficial action of self-weight which is present in vertically oriented elements.

Because the specimen was statically determinate, the only path of loads was through the wall. The capacity of the specimen was therefore limited by a ductile flexural failure at the base of the wall; this failure was manifested by widening of existing flexural cracks at that location. Displacement ductility factor of the specimen at failure was 7.

Fig. 7 depicts the deflection profiles in the slab and wall associated with shear deformations; it is evident that although both slab and wall were planar diaphragms subjected to in-plane shear and a bending moment linearly increasing from the tip of each element towards its respective support, the two demonstrated significantly different behaviours. This is believed to be primarily the result of the different boundary conditions of the two elements. Because of the restraining which was provided to the wall by the slab, the pattern of cracking in the wall was completely different from what is commonly observed in single wall tests, where cracking primarily is concentrated in the region of maximum flexural moment at the base (Figs. 8a and 8b). It is believed that this result is of particular importance in evaluating experimental data obtained from tests of single isolated walls loaded by direct actions rather than being subjected to the indirect diaphragm action which is provided by the slab in actual structures.

At low levels of lateral displacement, the in-plane shear forces were essentially transferred uniformly from the slab to the wall through the connection. This was evident from the formation of a uniform cracking pattern along the wall side of the connection (Fig. 8b). However, at higher levels of lateral displacement, as the horizontal flexural cracks along the connection became wider, it is believed that the transfer of shear forces occurred largely in the flexural compression zone of the connection. This is apparent from the distribution of tensile stresses in the longitudinal slab reinforcement plotted in Figs. 9a and 9b. (The stresses were computed from the measured strain histories of the reinforcement using the hysteretic stress-strain model for reinforcing steel proposed by Menegotto and Pinto (1977)). It can be seen from those figures that the tensile stress difference between two adjacent cross-sections in a single bar was approaching zero as the lateral displacement was increased. This suggests that the contribution of the flexural tension region of the connection in transferring in-plane forces from the slab to the wall was practically very small.

CONCLUSIONS

The mechanism of shear transfer at slab-wall connections subjected to cyclic lateral loads was investigated. The study included data from an experimental investigation of an interior slab-wall connection tested at the University of Toronto, under combined vertical and lateral loads simulating earthquake effects. Data from other related tests were also considered when applicable. Results of the study are as follows:

1. Although the pattern of in-plane actions was similar in the slab and the wall, the two elements exhibited different behaviours in response to the applied lateral loads; these differences are believed to have resulted from the action of gravity loads on the slab, and from the different displacement constraints present in the two elements.

2. The experiment revealed that vertical loads affect the in-plane stiffness and shear resistance of the floor-slabs particularly in the vicinity of the slab-wall connection. The available experimental evidence also indicates that vertical shear forces generated from gravity loads reduce the in-plane shear resistance of the slab at critical boundaries where top or bottom longitudinal slab reinforcement is cut-off (points of zero gravity moment).

3. Widening of flexural cracks at the slab side of the connection at high levels of displacement was observed to cause redistribution of shear forces along the connection. The in-plane shear resistance of slab-wall connections at the vertical face of the support is limited to approximately $0.25\sqrt{f'_c}$ Mpa; in all test cases considered, experimentally obtained shear resistances were only 60% of the nominal values computed using the ACI Code equations (1983).

ACKNOWLEDGMENTS

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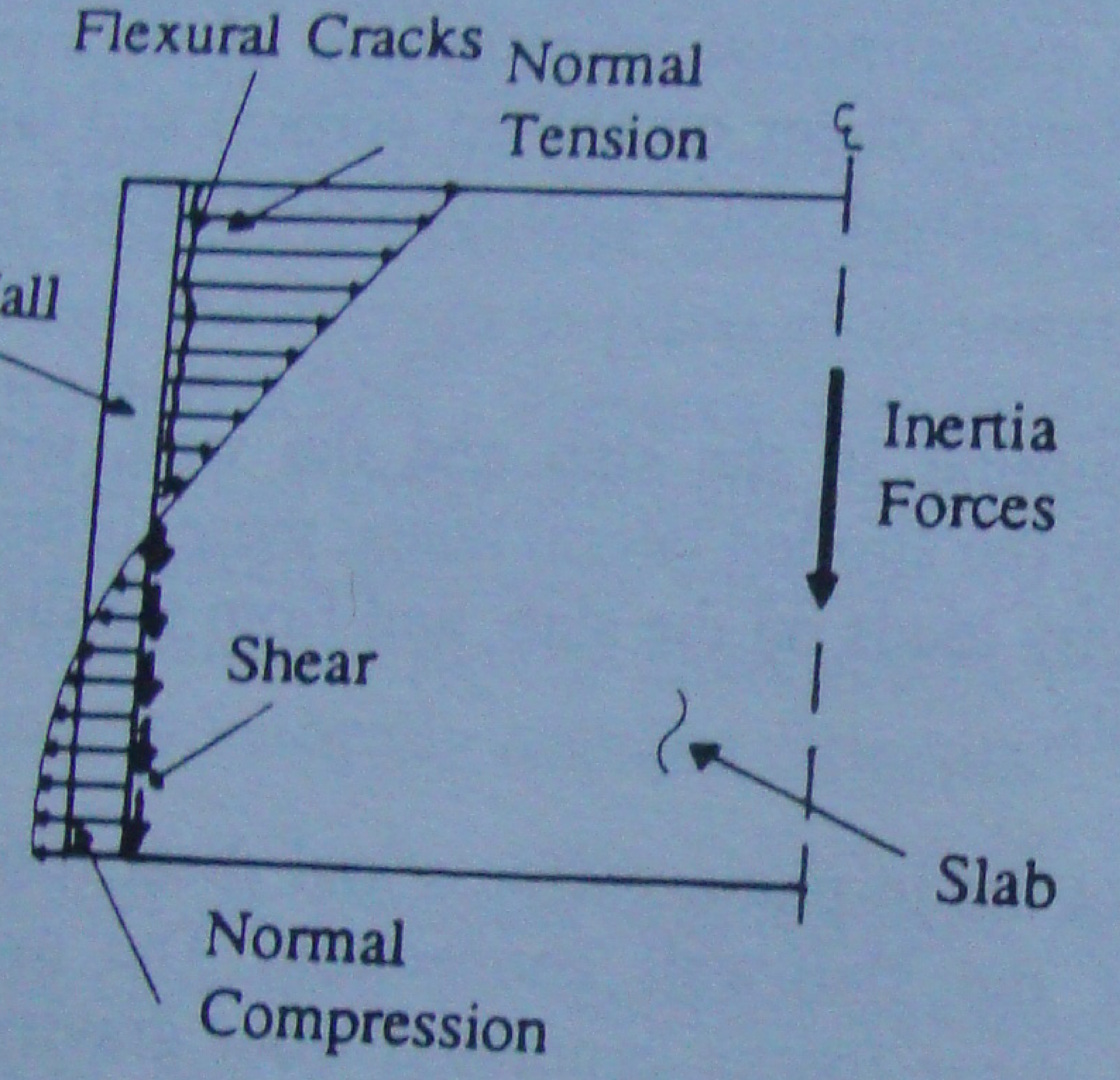


Figure 1. Deep beam action in the slab

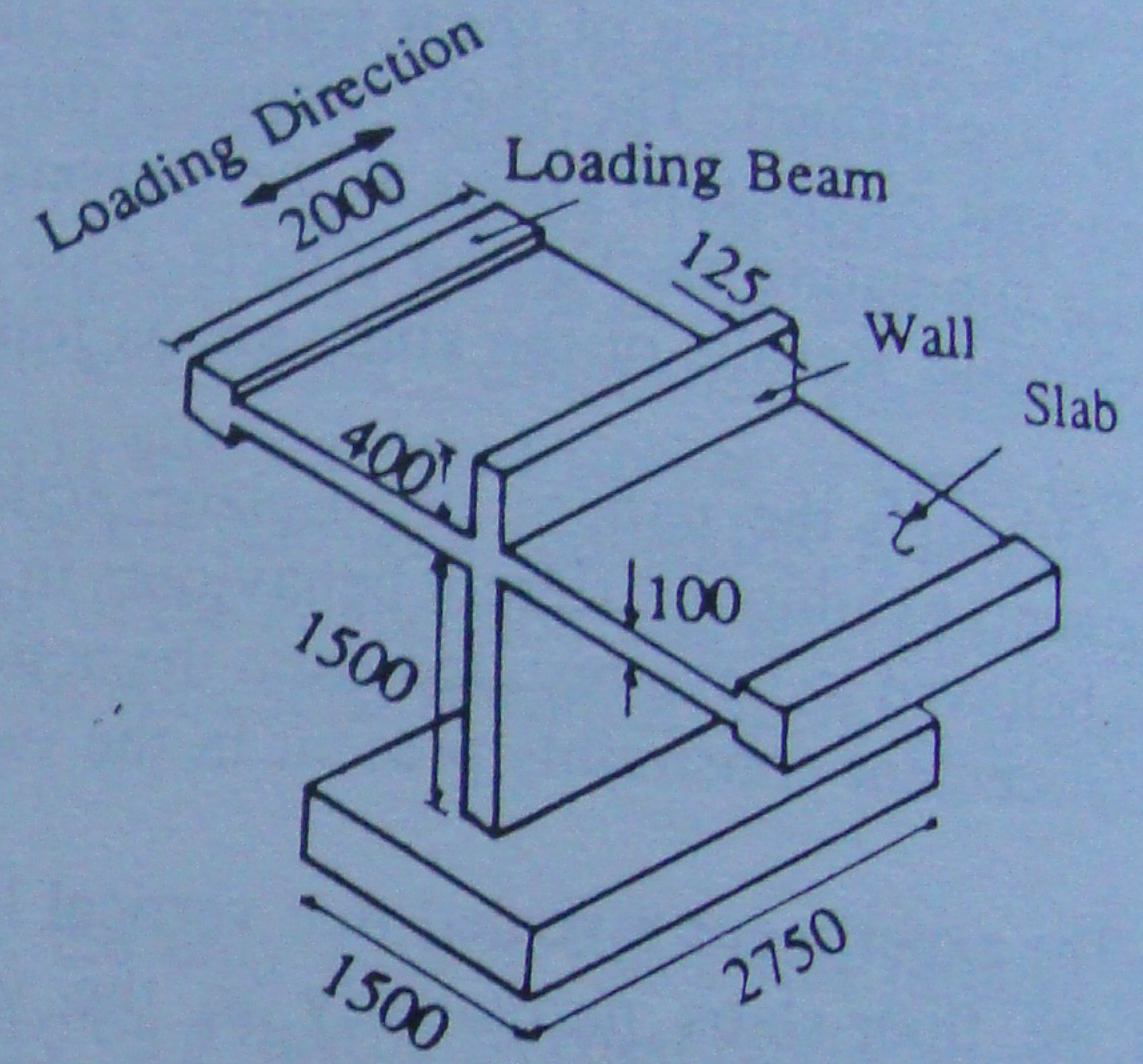


Figure 2. View of specimen

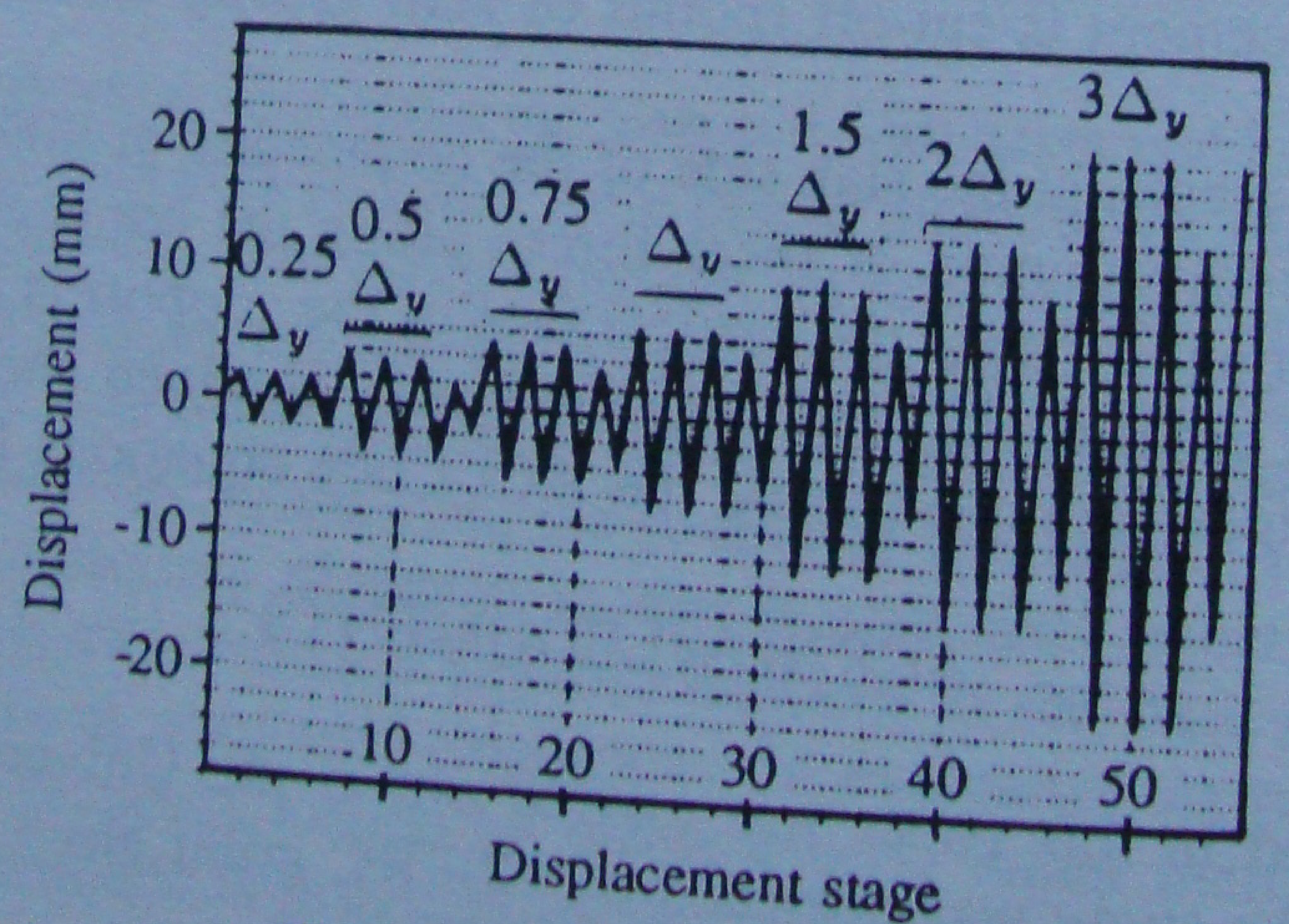


Figure 3. Displacement history

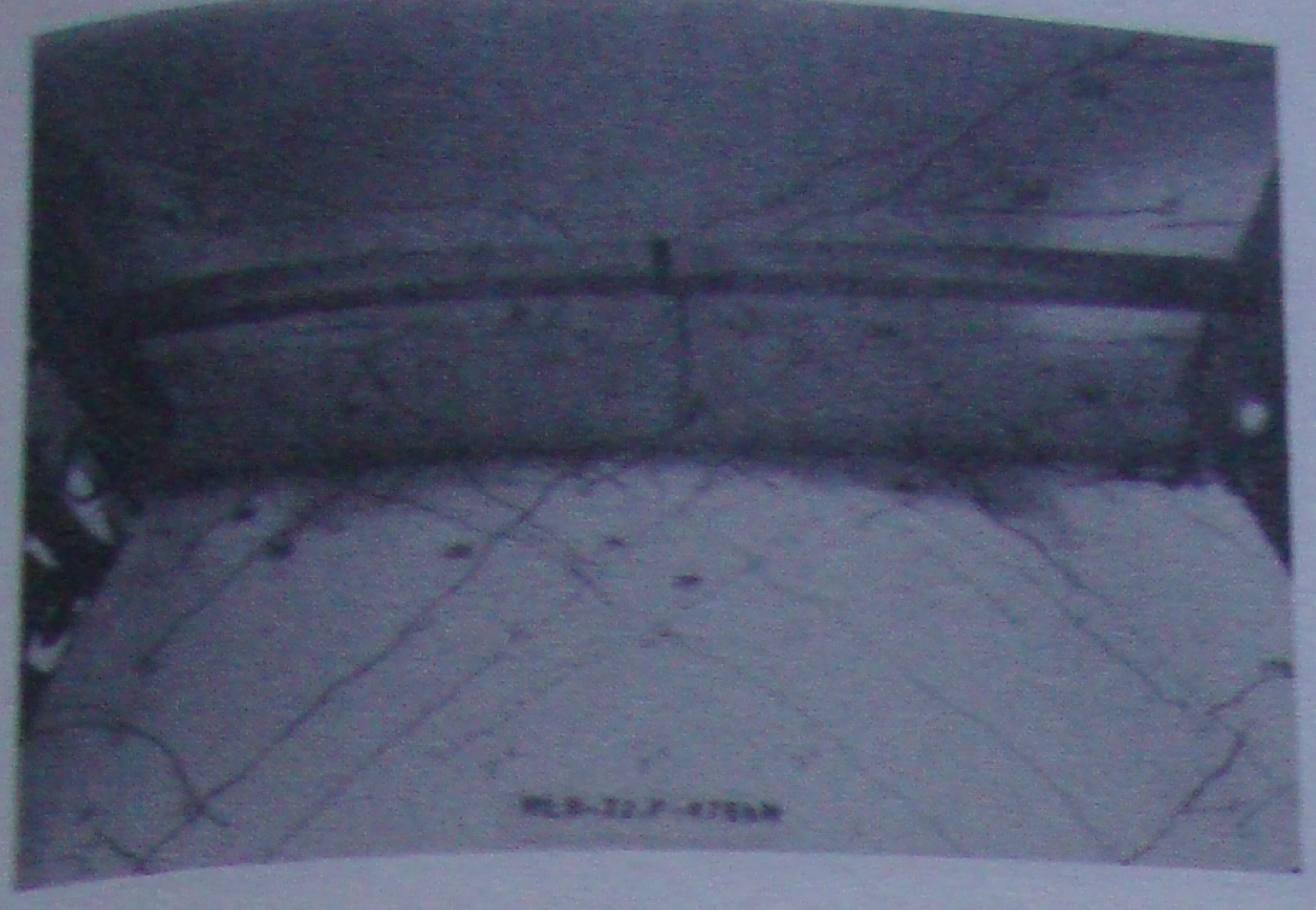


Figure 4. Cracking pattern at connection

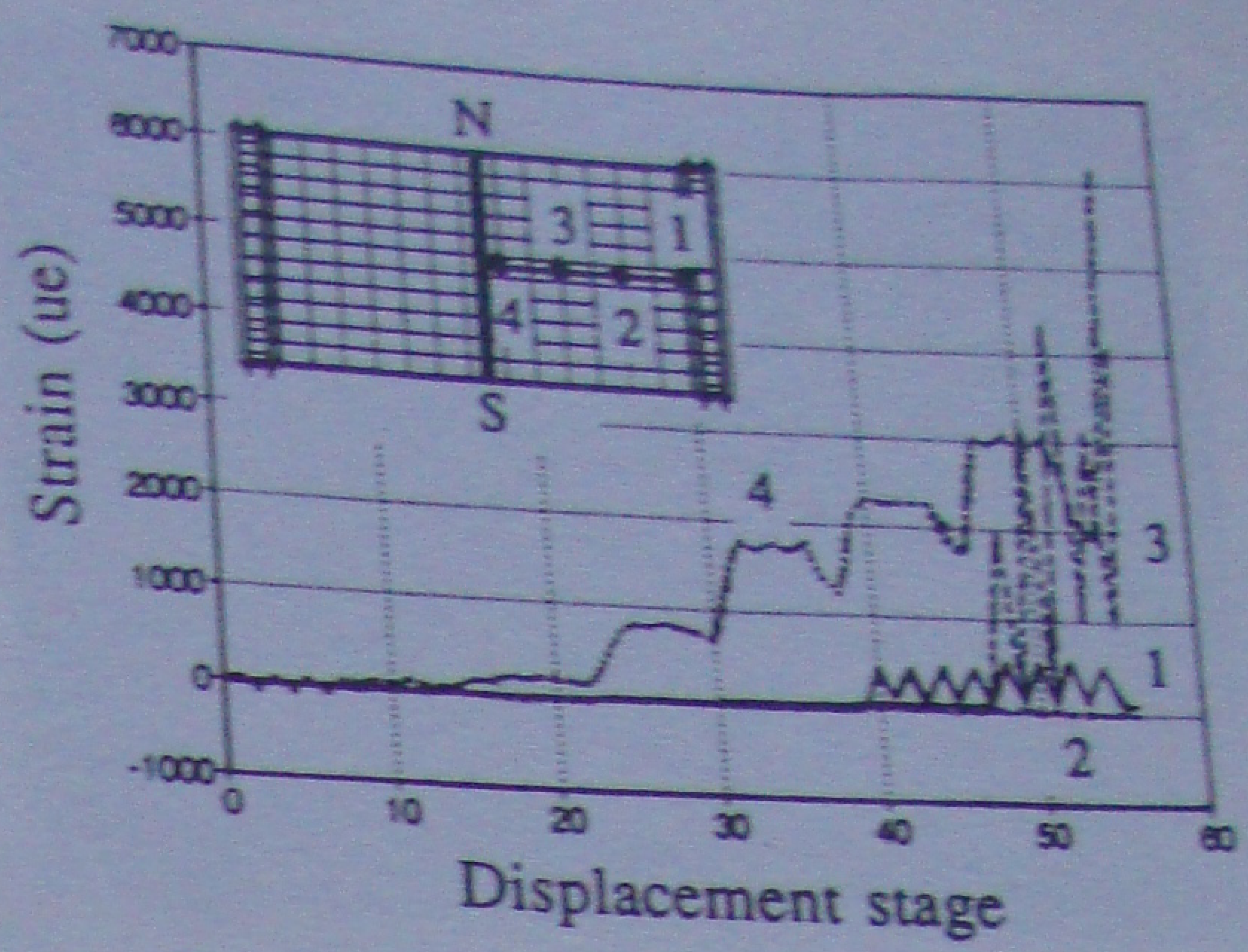


Figure 5. Strain history of transverse slab reinforcement

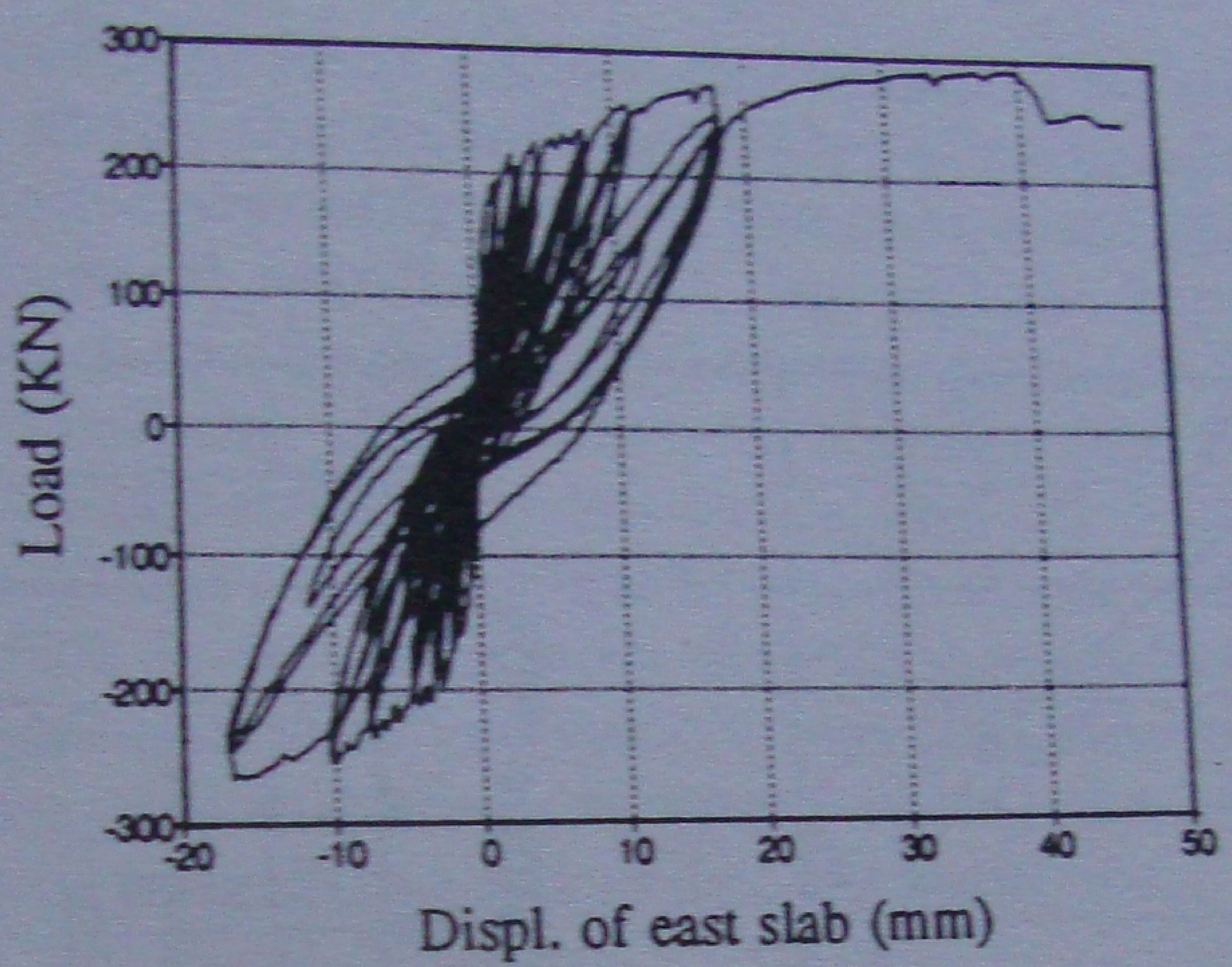
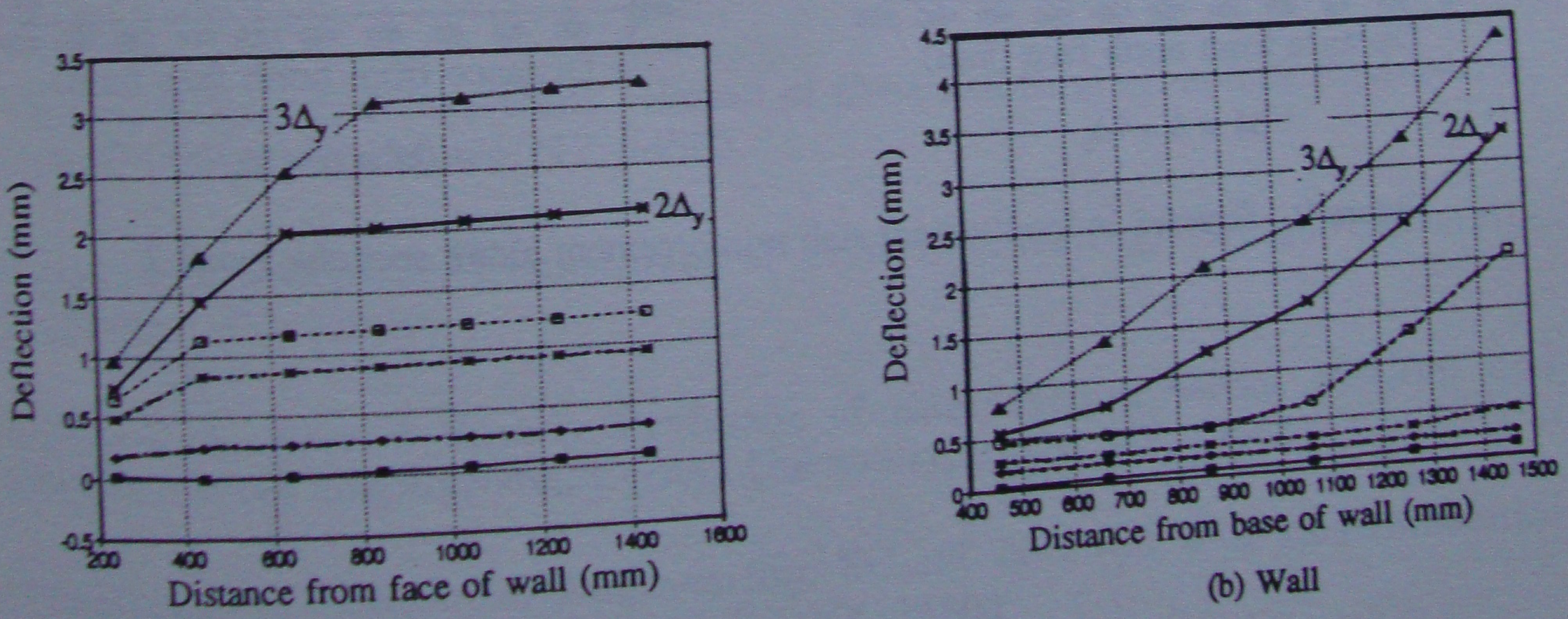


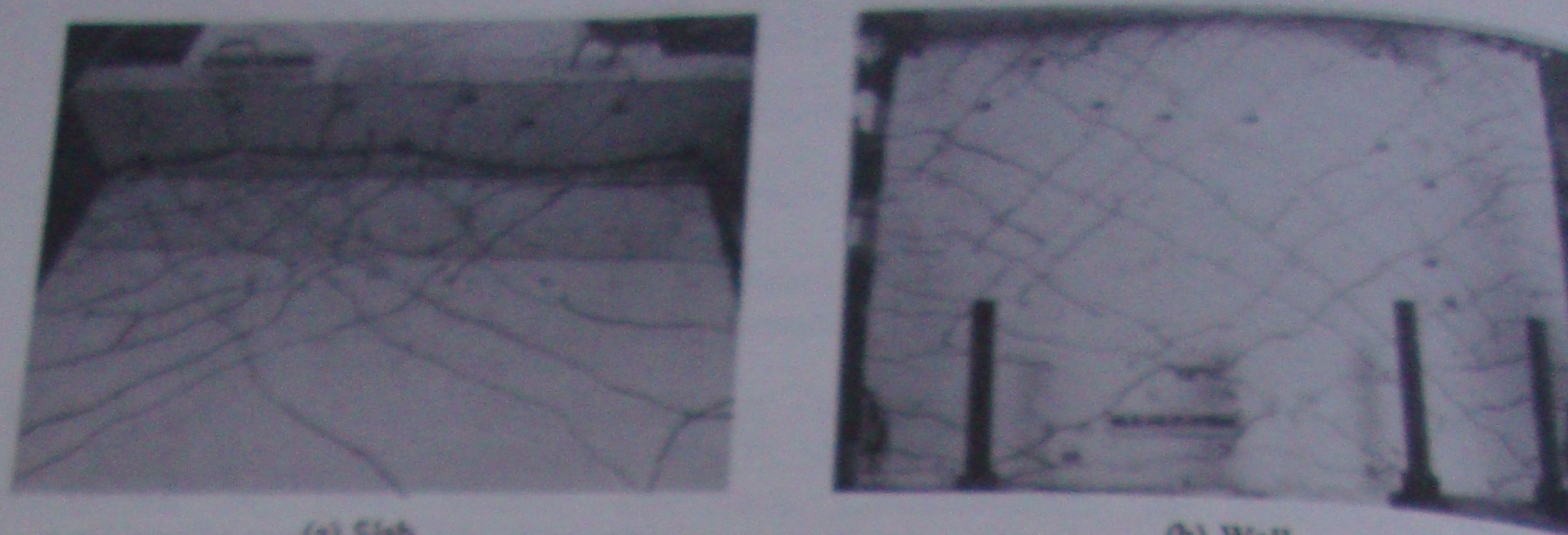
Figure 6. Total load-displacement curve



(a) Slab

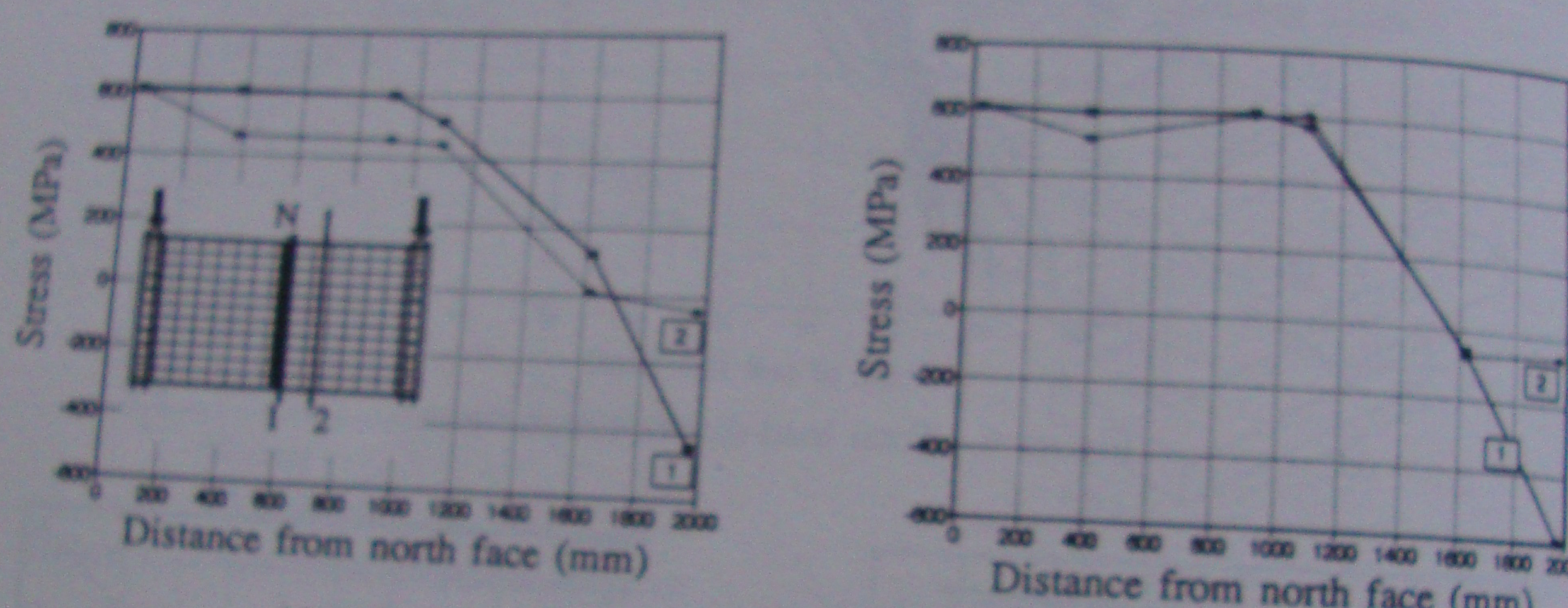
(b) Wall

Figure 7. Lateral deflections associated with shear



(a) Slab (b) Wall

Figure 8. Cracking patterns in specimen



(a) at $\Delta = 2\Delta_y$ (b) at $\Delta = 3\Delta_y$

Figure 9. Stresses in longitudinal slab reinforcement along sections 1 and 2