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# Experimental studies on the inelastic behavior of reinforced concrete panels under high-speed loading Part 2. Effects of rebar ratio and lap splices

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## Abstract

As described in Part 1, the objectives of the present study are to experimentally investigate the effects of rebar ratio and lap splices on the inelastic behavior of reinforced concrete (RC) panels subjected to an impact load. Six experiments were conducted using rectangular RC panel specimens with parameters of reinforcement ratio (0.47% and 0.24%) and position of lap splices. The length of lap splices adopted in the experiments was 48d (d: diameter of rebars). Experimental results show that, compared with standard panels (0.47%, no lap splices), (1) panels with reduced reinforcement (0.24%) showed even greater ductility and (2) no significant deterioration of the strength of RC panels with lap splices was found beyond the maximum load point. It is expected that the results will lead to greater efficiency and flexibility in the design and construction of RC members subjected to an impact load.

# 1 Introduction

When designing reinforced concrete (RC) structures subjected to an impact load in practice, some important design parameters must be considered, such as panel thickness, reinforcement ratio and rebar joint details. Of these, the effects of rebar ratio and adoption of lap splices for rebar joints are the main interests in the present study as described in Part 1[1].

# 2 Experiments

## 2.1 Test cases

Experimental parameters and test cases are listed in Table 1. Test cases No.3 and No.4 (MR50 series) are adopted to investigate the effects of reduced reinforcement ratio by comparing their results with those of standard cases, No.1 and No.2 (STD series), which have already been tested in Part 1. Test cases No.5 through No.8 are for investigating the applicability of lap splices in RC panels subjected to an impact load.

## 2.2 Specimens

Figure 1 shows typical reinforced concrete specimens, MR50 series and $LS75_H$. The overall specimen dimensions are 240cm x 210cm x 20cm and the diameter of a load introduction plate is 43cm, both of which are approximately 1/6 scaling of a real RC structure and loading, respectively. The rebars and concrete are basically the same as those used in Part 1. The material properties of the rebars and concrete on each testing date are listed in Table 2.

## 2.3 Apparatus

High-speed and static loading tests were performed by using a servo-hydraulic impact testing machine at BAM. The functions and capacities of this machine are explained schematically in Part 1 and in Limberger and Struck[2]. An out of plane concentrated loading was applied at the center of the specimen until the center displacement reached its preset stroke limit of 180mm. In the high-speed loading tests, the loading was controlled at the constant displacement rate of 200cm/s which was

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analytically determined as the typical response of the real scale RC panel subjected to the aircraft impact load.

### 2.4 Measurements

Loads, deflections, rebar and concrete strains, accelerations and high-speed photography are among main measurement items. The details are shown in Part 1.

## 3 Results and discussion

### 3.1 Failure modes of RC panels

Top, bottom and side views of damaged RC panels for $MR50_H$ and $LS75_H$ after the loading was completed are shown in Fig. 2. The deference in crack intervals at the bottom surface is dependent on the rebar mesh arrangement of each specimen. The failure mode of both panels at this stage of deflection 180mm, which is well beyond the design level of the RC panel against an aircraft impact load, was flexural failure with cover concrete removed along the yield line at the center of the long span. The local penetrations at the edge of the load introduction plate after primary flexural failure of the RC panel were found in some cases. These failure modes are consistently the same for all cases including the reference cases: STD series.

### 3.2 Effects of reinforcement ratio

The main experimental results for all cases are tabulated in Table 3, i.e. loads $P$, deflections $\delta$, rebar strains $\varepsilon$ and ductility factors $\delta/\delta_y$ at the point of the initial rebar yield, the maximum load and unloading. The ductility factors are defined as a ratio of a deflection at a corresponding point to the deflection at the initial rebar yield, that was determined as a point where the rebar strain gauge record reaches to the static yield point of a rebar, 2085μ, for the first time in each test. The results at the unloading point may be referred values to evaluate the ductile behavior of each panel beyond the maximum load point.

Load-deflection curves of specimens with a rebar ratio of 0.24% (MR50) are compared with those of 0.47% (STD) in Fig. 3, where

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dynamic effects due to an inertial force on the load measurements have been compensated and smoothing by Hamming's lag-time window has been achieved as described in Part 1. The rebar ratio in the present paper is defined as the ratio of the total area of nominal rebar sections for one way in one layer, i.e. in a top or bottom layer, to the entire concrete section.

In Fig. 3, both STD and MR50 show stable and ductile load-deflection curves beyond the maximum load points up to the unloading points due to the stroke limit, where the ductility factors are more than 20 and still greater than approximately 70% of the maximum load is sustained by those panels (see Table 3). The strength of MR50 is of course almost half of that of STD because of the reduction of reinforcement by 50%. It is also found in Table 3 that the ductility factor of $MR50_H$ at the maximum load, 20, is very large: much greater than 11 and 9 for $MR50_S$ and $STD_H$, respectively.

The experimental results show that an RC panel with 0.24% reinforcement has greater ductility against both high-speed and static loading than the one with 0.47% reinforcement. RC structures subjected to an impact load, therefore, can be designed by using the minimum rebar ratio of 0.24% as long as the other design criteria are satisfied.

### 3.3 Effects of lap splices

Load-deflection curves for specimens without/with lap splices are shown in Fig. 4. It should be noted here that the effective depth of $LS50_H$ and $LS100_H$ for bending (180mm) is slightly (6%) greater than that of the other specimens (170mm), since the bottom rebars of $LS50_H$ and $LS100_H$ are located outside to enable observation of the behavior of critical lap splices (i.e. a layer of lap splices newly added to the corresponding specimen) in bending by aligning them in the long span direction. The effective depth is defined as the distance from the center of the rebars in tension to the concrete surface in compression. In the present study, a rather long lap splice length of 48d (d: nominal diameter of rebars) is chosen compared with that used in conventional RC structures. This is determined to provide sufficient panel-ductility beyond the rebar yield point at an ultimate stage and to take into account the dynamic increase effects on the rebar yield strength.

From Fig. 4, it is obvious that all specimens with lap splices up to 100% layers (LS series) basically show very ductile load-deflection curves beyond the maximum load point. They sustain almost greater than 70% of their maximum load even at the unloading points where the ductility

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factors reach 21~32 as shown in Table 3. The ductility factors of all specimens with lap splices (LS series) are 7 to 9 at the maximum load. These are comparable with the ductility factor, 9, of $STD_H$. These load-deflection curves of the panels with lap splices are almost comparable with that of the standard case without lap splices ($STD_H$). The bearing capacity of $LS100_H$, however, seems to decline slightly earlier from the maximum load point than those of the others. It is considered that this is mainly due to the thickness of the cover concrete, 15mm or 1.5d, for the lap splices at the bottom rebars of $LS100_H$ along the long span direction, which is smaller than 25mm or 2.5d of $LS75_H$.

Figure 5 shows rebar strains of top rebars of $LS25_H$ and $LS50_H$ which have critical lap splices in the top rebar mesh, and of bottom rebars of $LS75_H$ and $LS100_H$ which have critical lap splices in the bottom rebar mesh. Of these, S1, S4, S6, S10, S13 and S15 are located at the end of lap splices as well as on the yield line of each panel. As shown in Fig. 5 (1), the top rebar strains remain below the yield point (2085μ, static) up to the maximum load point (see Table 3 and Fig. 4), except S4 of $LS25_H$ of which peak strain reaches 2759μ at $\delta$ =60mm. The strain gauges S6 of both $LS25_H$ and $LS50_H$ show relatively large negative (compression) strains after the point of the cover concrete failure (see Fig. 4).

Figure 5 (2) shows that some bottom rebar strains reach extremely high levels of up to 90000μ. It suggests the lap splices under the present testing conditions can withstand the tensile force corresponding to those strain levels occurred at the rebar. On the other hand, the strains of S10 of $LS75_H$ and $LS100_H$ do not increase much beyond the maximum load points (see Table 3 and Fig. 4) and the strain levels of 50000μ and 30000μ, respectively. These phenomena of the limited rebar strains, however, seem to occur within the very localized area beneath the load introduction plate, and could be due to the local damage produced by the edge of the rigid load introduction plate which may not reproduce a realistic loading situation by the soft missile impact such as an aircraft. The load-deflection curves of $LS75_H$ and $LS100_H$ are not affected much by those phenomena as already discussed earlier in this section and shown in Fig. 4.

Based on the above experimental results, the lap splices should be able to be used in RC panels subjected to an impact load as a practical option for rebar joints.

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# 4 Concluding remarks

Conclusions of the present experimental study are summarized as follows.

(1) An RC panel with 0.24% reinforcement has greater ductility against both high-speed and static loading than the one with 0.47% reinforcement. RC structures subjected to an impact load, therefore, should be able to be designed by using the minimum rebar ratio of 0.24%.

(2) The load-deflection curves of the panels with lap splices are very ductile and show no significant deterioration of the strength of RC panels beyond the maximum load points up to the unloading points (ductility factors: $\delta_{ul}/\delta_y$ = 21~32) compared with that of the standard case without lap splices. The rebar strains at the end of lap splices reach extremely high levels of up to 90000μ, suggesting the lap splices can withstand the tensile force corresponding to those strain levels occurred at the rebar. Accordingly, the lap splices (48d) used in the present study should be able to be used in RC panels subjected to an impact load as a practical option for rebar joints.

It is expected that the results of the present study will lead to greater efficiency and flexibility in the design and construction of RC structures subjected to an impact load.

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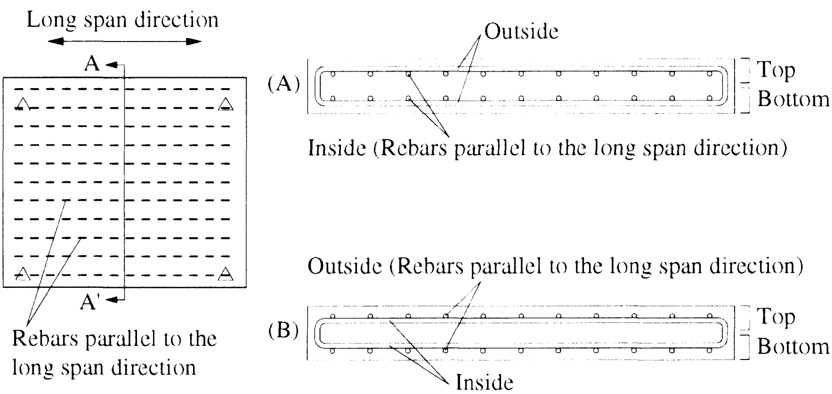
Table 1 Experimental parameters and cases

| No. | Test name | Rebar ratio | Lap splices | Rebar arrangement type *2 | Loading rate | Remarks |
|---|---|---|---|---|---|---|
| 1 | STD$_H$*1 | 0.47% | none | (A) long span inside | 200cm/s | standard |
| 2 | STD$_S$*1 | 0.47% | none | (A) long span inside | 0.1mm/s | |
| 3 | MR50$_H$ | 0.24% | none | (A) long span inside | 200cm/s | reduced rebar ratio (50%) |
| 4 | MR50$_S$ | 0.24% | none | (A) long span inside | 0.1mm/s | |
| 5 | LS25$_H$ | 0.47% | top inside (25%) *2 | (A) long span inside | 200cm/s | lap splices |
| 6 | LS50$_H$ | 0.47% | top inside & outside (50%) | (B) long span outside | 200cm/s | |
| 7 | LS75$_H$ | 0.47% | top inside & outside, bottom inside (75%) | (A) long span inside | 200cm/s | |
| 8 | LS100$_H$ | 0.47% | top inside & outside, bottom inside & outside (100%) | (B) long span outside | 200cm/s | |

*1) These cases are investigated in Part 1 [1].

*2) Rebar designation




Panel specimen A-A' Section

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Table 2 Material properties (Static)

| | Test name | Compressive strength (MPa) | Young's modulus ($x10^4$ MPa) |
|---|---|---|---|
| concrete | $MR50_H$ | 39.5 | 2.22 |
| | $MR50_S$ | 27.8 | 2.24 |
| | $LS25_H$ | 31.9 | 2.04 |
| | $LS50_H$ | 32.1 | 2.16 |
| | $LS75_H$ | 28.3 | 2.17 |
| | $LS100_H$ | 29.1 | 2.09 |

| | Nominal diameter, area | Yield strength (MPa) | Young's modulus ($x10^5$ MPa) |
|---|---|---|---|
| rebar *1 D10 SD345 (JIS) | 10 mm, 0.71 $cm^2$ | 382 | 1.87 |

*1) A stress-strain curve of the rebar is shown in Part 1 [1].

Table 3 Experimental results

| Test name | Initial rebar yield | | Max. load | | | | Unloading point due to the stroke limit | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | load $P_y$ (kN) | deflec. $\delta_y$ (mm) | load $P_m$ (kN) | deflec. $\delta_m$ (mm) | ductility factor $\delta_m / \delta_y$ | max. bottom rebar strain $\varepsilon_m$ ($\mu$) | load $P_{ul}$ (kN) | load reduction ratio $P_{ul} / P_m$ | deflec. $\delta_{ul}$ (mm) | ductility factor $\delta_{ul} / \delta_y$ | max. bottom rebar strain $\varepsilon_{ul}$ ($\mu$) |
| $STD_H$ *1 | 272 | 7.9 | 417 | 67.9 | 9 | 37430 | 339 | 0.81 | 162.6 | 21 | 78480 |
| $STD_S$ *1 | 269 | 8.6 | 357 | 57.8 | 7 | 34670 | 245 | 0.69 | 179.0 | 21 | 56670 |
| $MR50_H$ | 139 | 5.8 | 246 | 114.2 | 20 | 53870 | 178 | 0.73 | 170.6 | 29 | — |
| $MR50_S$ | 137 | 7.3 | 188 | 81.4 | 11 | 50270 | 160 | 0.85 | 182.7 | 25 | 82740 |
| $LS25_H$ | 249 | 8.1 | 396 | 57.4 | 7 | 35430 | 341 | 0.86 | 169.8 | 21 | 80430 |
| $LS50_H$ | 264 | 7.3 | 414 | 58.9 | 8 | 41520 | 310 | 0.75 | 168.9 | 23 | 72260 |
| $LS75_H$ | 262 | 6.2 | 413 | 54.5 | 9 | 46340 | 305 | 0.74 | 181.6 | 29 | 77780 |
| $LS100_H$ | 281 | 5.3 | 367 | 37.4 | 7 | 44450 | 255 | 0.66 | 170.1 | 32 | 84720 |

*1) These cases are investigated in Part 1 [1].

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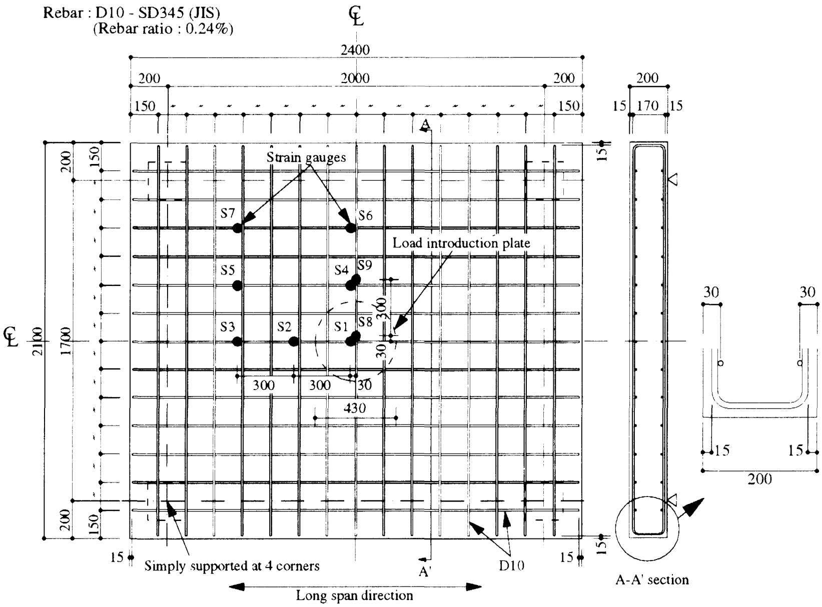
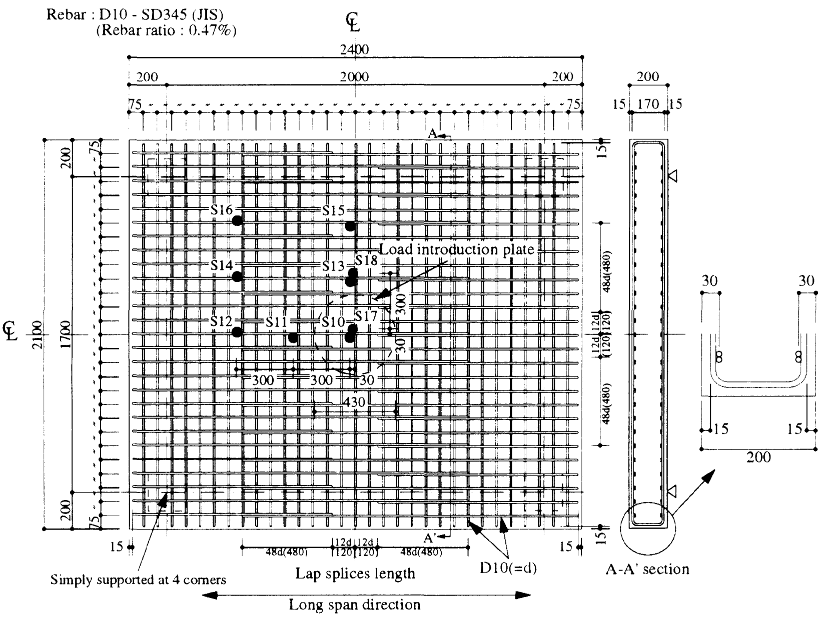
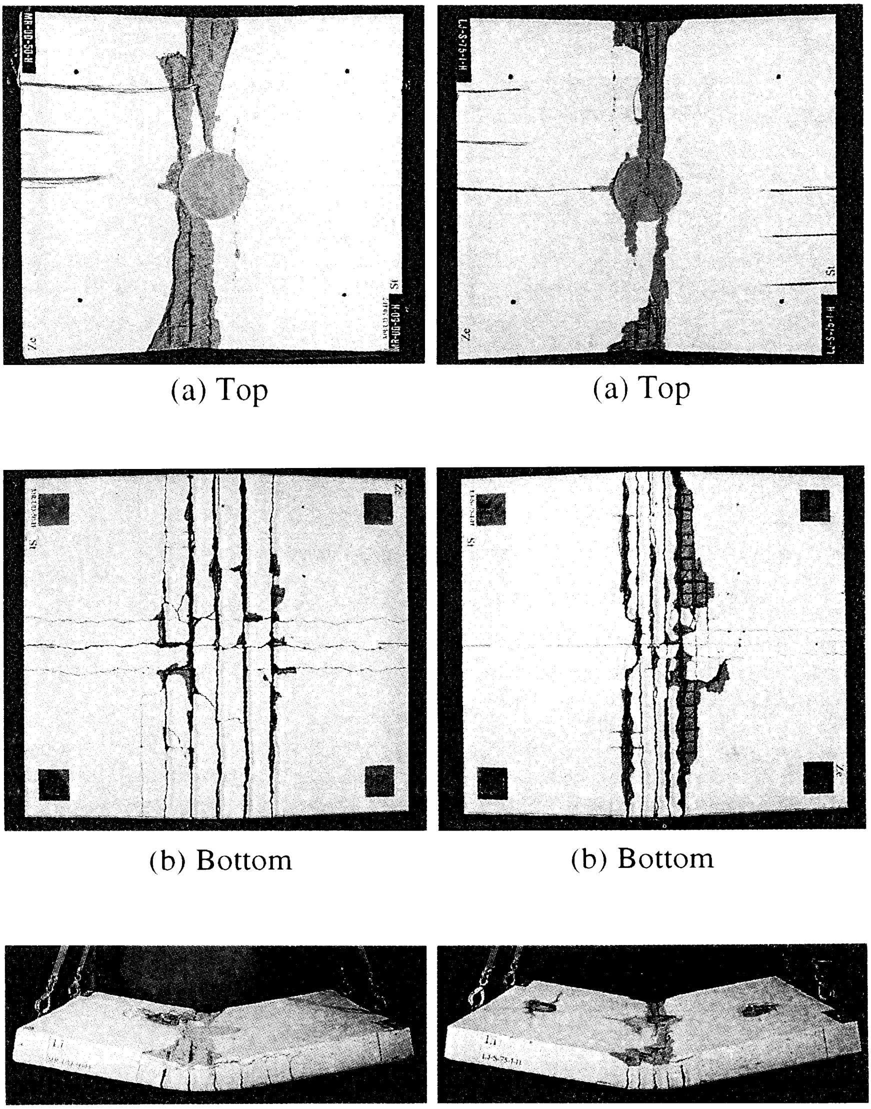



(1) MR50 (Top & Bottom layers)




(2) $LS75_H$ (Bottom layer)

Fig. 1 RC panel specimens and location of rebar strain gauges (Unit : mm)



(a) Top (a) Top

(b) Bottom (b) Bottom

(c) Side (c) Side

(1) $MR50_H$ (2) $LS75_H$

Fig. 2 Failure mode of RC panels after loading

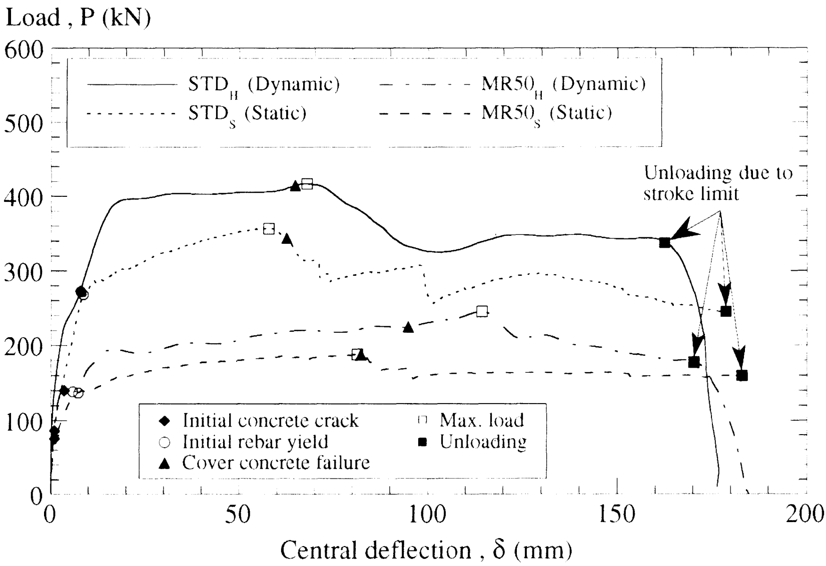



Fig. 3 Load-deflection curves with variation of rebar ratio and loading rate.

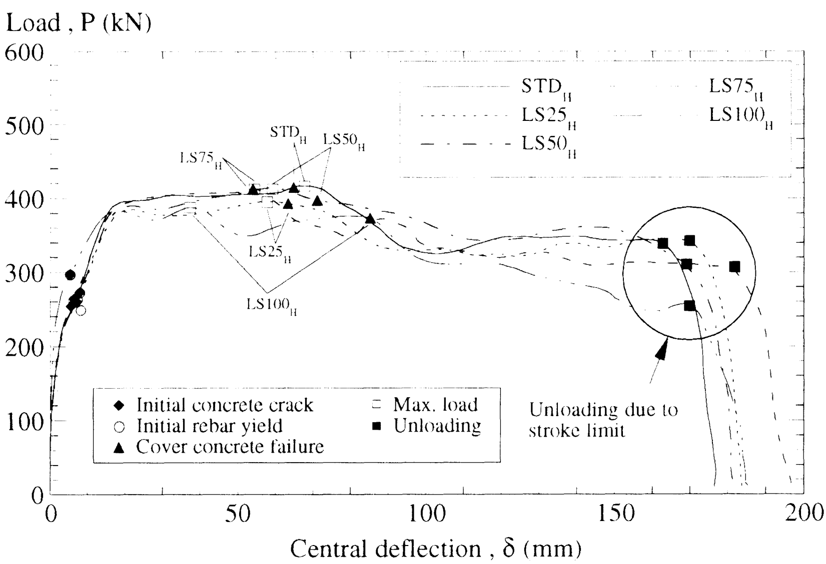



Fig. 4 Load-deflection curves with variation of lap splices

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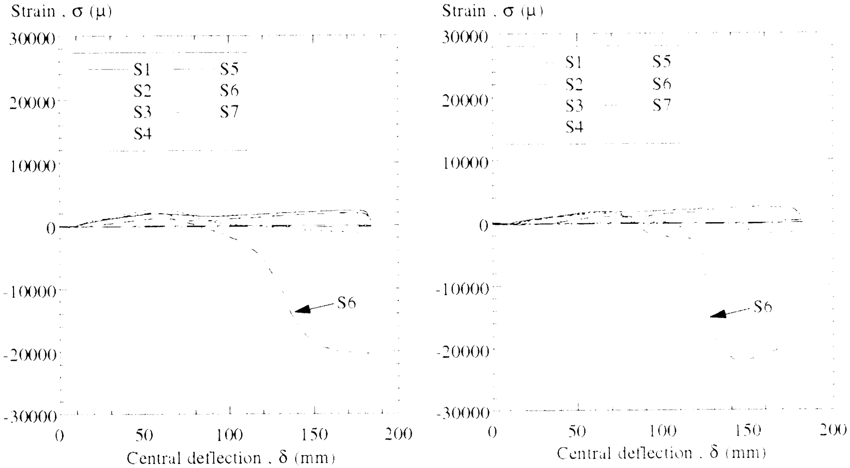
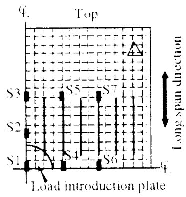
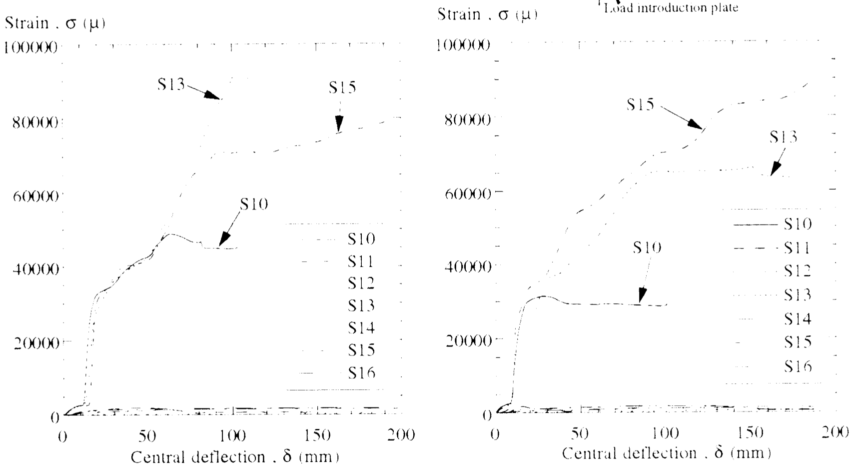


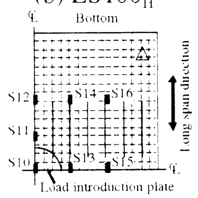

(a) $LS25_H$ (b) $LS50_H$




(1) Rebar strains in a top layer.




(a) $LS75_H$ (b) $LS100_H$




(2) Rebar strains in a bottom layer.

Fig5. Variation of rebar strain with central deflection