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# Reinforcing Method for R/C Suspended Slabs Connected to a Bottom Flange of H-shape Steel Beam

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## Summary

In order to propose a better reinforcing method for reinforced concrete (R/C) suspended slabs connected to the bottom flange of the steel H-shape beams in the steel building structure, nine full scale specimens with different slab-to-beam connection details were tested under monotonic vertical loading. Test results indicate that, in cases, where the bottom flange of the H-shape steel beam is located within the R/C floor slabs, special diagonal reinforcing bars are quite effective to prevent the occurrence of the brittle shear failure and to increase the ultimate strength of the inverted T-shape suspended slabs. Furthermore when the bottom flange of the H-shape steel beam is located at the bottom surface of the R/C slabs, suspended slabs can develop their flexural moment capacities and excellent deformation capacities as good as the ordinary T-shape floor slabs. In addition, supplemental top reinforcing bars are effective enough to provide the much higher strength of the inverted T-shape suspended slabs.

## 1. Introduction

A new type of building structure with double floor slab system as shown in Fig. 1 was first proposed by the authors more than ten years ago. Using this concept, the first R/C residential building with seven stories was built in 1994 in Oita City, Japan and the first steel reinforced concrete (SRC) residential building with eleven stories was built in 1996 in Fukuoka City, Japan. Top floor of this double-floor system is a lumber decking which is composed of plywoods and light-gauge steel sub-beams without any intermediate supports. On the contrary, bottom floor of this double-floor system is an R/C suspended slab which has an inverted T-shape or L-shape cross-section at the slab-to-beam connections. This double floor slab system can insulate the sound transmission from upper-story residents, and provides satisfactory storage spaces for household effects between top and bottom floor slabs.

Although this type of double-floor slab system is expected to be adopted to the multi-story residential, office and hospital building floor systems for steel structures as well as R/C and SRC building structures, systematic experimental studies on the effect of reinforcing details on its structural behavior have not been conducted sufficiently. In the past experimental studies conducted by the authors for developing a better reinforcing details for R/C suspended slab connected to R/C and SRC beams with inverted T-shape, some of the slabs with inadequate reinforcements showed much poorer structural behavior than ordinary T-shape slabs [1, 2, 3].

Main objective of the present study is to examine the structural behavior of inverted T-shape reinforced cast-in place concrete suspended slabs connected in fixed support condition to steel H-shape beam experimentally and to propose a better reinforcing method for strength and ductility of this type of suspended slabs. In the present experimental study, eight different full-scale specimens with inverted T-shape slabs were tested under monotonic vertical loading and test results were compared with those obtained from the ordinary T-shape specimen.

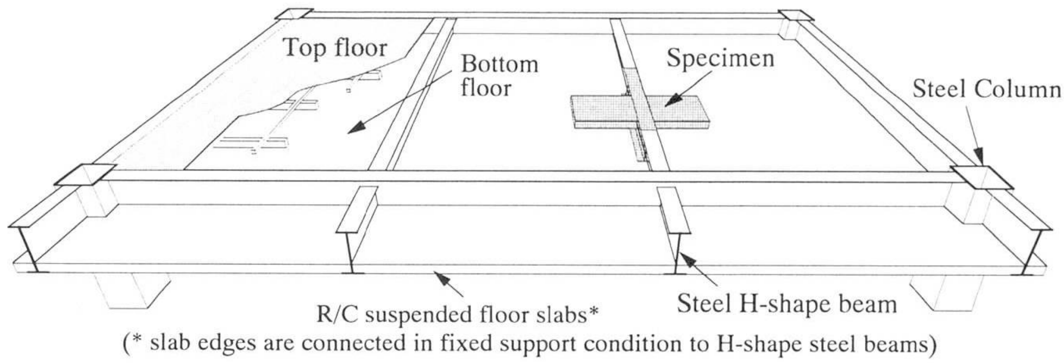


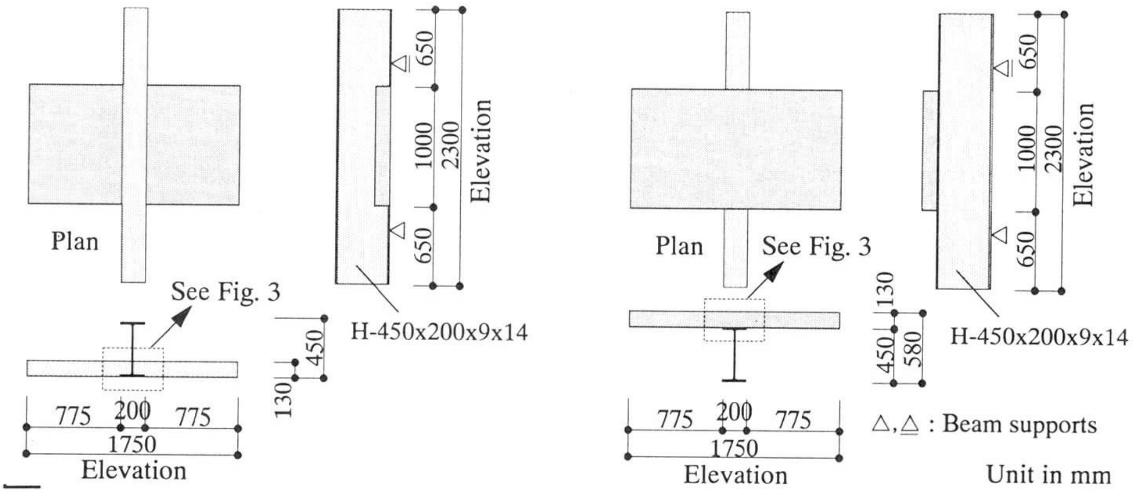

*Fig. 1 Double-floor slab system*

## 2. Test Specimens

A total of nine full-scale specimens with different slab-to-beam connection details were designed and constructed. Eight specimens have the suspended slabs with inverted T-shape cross-sections, and only one specimen has an ordinary T-shape cross-section. Each specimen is composed of one steel H-shape beam element and two R/C slab elements connected to each other along the top flange of the steel beam for the T-shape specimen and the bottom flange of the beam for the inverted T-shape specimens, respectively. Fig. 2 shows size and shape of the typical specimens, which correspond to the slab-beam assemblages as shown in Fig. 1. Reinforcing details for all specimens are listed in Table 1 together with the material properties of the concrete and reinforcing bars, and the slab-to-beam connection details of all specimens are shown in Fig. 3. Inverted T-shape specimens are classified into two groups according to the location of bottom flange of the steel H-shape beams. Bottom flange of the steel H-shape beams for S-ITM Group specimens is located within the R/C floor slabs. While in case of S-ITB Group specimens, bottom flange of the steel H-shape beams is located at the bottom surface of the R/C slabs.

Specimen S-OT is a model of ordinary T-shape beam-slab subassemblage (where floor slabs are designed considering an ordinary T-shape slab system), where required amount of reinforcement and connection details are designed in accordance with the current structural design standard in Japan [4].

Other eight specimens are inverted T-shape specimens with different slab reinforcements and slab-to-beam connection details. Specimen S-ITM has the same slab reinforcements with specimen S-OT except that the slabs are located at the bottom of the steel beam, where the top reinforcing bars pass through the holes in the web plate of the steel H-shape beam section, and are continuous




*(a) Inverted T-shape specimen* *(b) Ordinary T-shape specimen*

*Fig. 2 Size and shape of test specimens*

*Table 1 Details of test specimens*

| Specimens | Reinforcements: Slabs: Top bars | Reinforcements: Slabs: Bottom bars | Reinforcements: Slab-to-beam connections: Top Re-bars | Reinforcements: Slab-to-beam connections: Bottom Re-bars | Reinforcements: Slab-to-beam connections: Diagonal Re-bars | Compressive strength of concrete [kgf/cm$^2$] | Yield strength of reinforcements: D13 (#4) [kgf/cm$^2$] | Yield strength of reinforcements: D10 (#3) [kgf/cm$^2$] |
|---|---|---|---|---|---|---|---|---|
| S-OT | D13 (#4) D10 (#3) Alternate @200 | D10 (#3) @400 | None | None | None | 269 | 3540 | 3460 |
| S-ITM | | | None | None | None | 164 | 3920 | 3830 |
| S-ITM-D | | | | | D13 @250 | 246 | 3540 | 3460 |
| S-ITM-DD | | | | | 2-D13 @250 | 252 | | |
| S-ITM-DB | | | | D13 @250 | D13 @250 | 261 | | |
| S-ITB30 | | | None | None | None | 221 | 3920 | 3530 |
| S-ITB42 | | | | | | 156 | | 3830 |
| S-ITB30-T | | | D13 @250 | | | 235 | | 3530 |
| S-ITB42-T | | | | | | 220 | | |

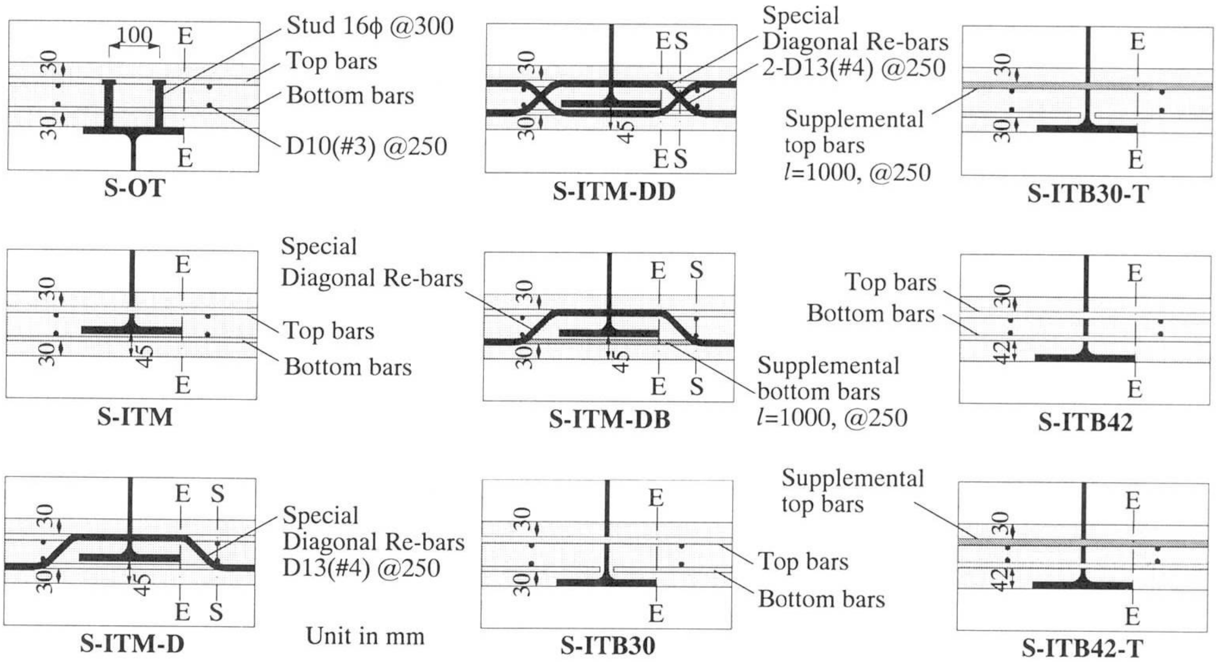



*Fig. 3 Reinforcing details in slab-to-beam connections*

throughout the left and right suspended slabs. In addition to this slab-to-beam connection detail, special diagonal and supplemental bottom reinforcing bars are provided in the specimens S-ITM-D, S-ITM-DD and S-ITM-DB as shown in Fig. 3 and Table 1.

Specimen S-ITB30 has the same slab reinforcements as specimen S-OT, however, bottom reinforcing bars of the slabs are not continuous across the web plate of the steel H-shape beam section, but extreme edges of these bars are placed close to the web plate surface as shown in Fig. 3. This is because it is not easy work to drill many holes around the web filet area of the ordinary rolled H-shape steel sections. While in specimen S-ITB42, bottom bars with a distance of 42mm from the bottom surface of the slab are provided continuously throughout the left and right suspended slabs as are the top reinforcing bars. In the specimens S-ITB30-T and S-ITB42-T, supplemental top bars are provided to the beam-to-slab connection details adopted respectively for the specimens S-ITB30 and S-ITB42.

## 3. Test Setups

Fig. 4 shows the test setup for inverted T-shape specimens. All the test specimens were simply supported at both ends of their steel H-shape beams. Vertical load to the slab-end, V, was applied as a concentrated line load, the loading point of which was 50 cm from the beam web.

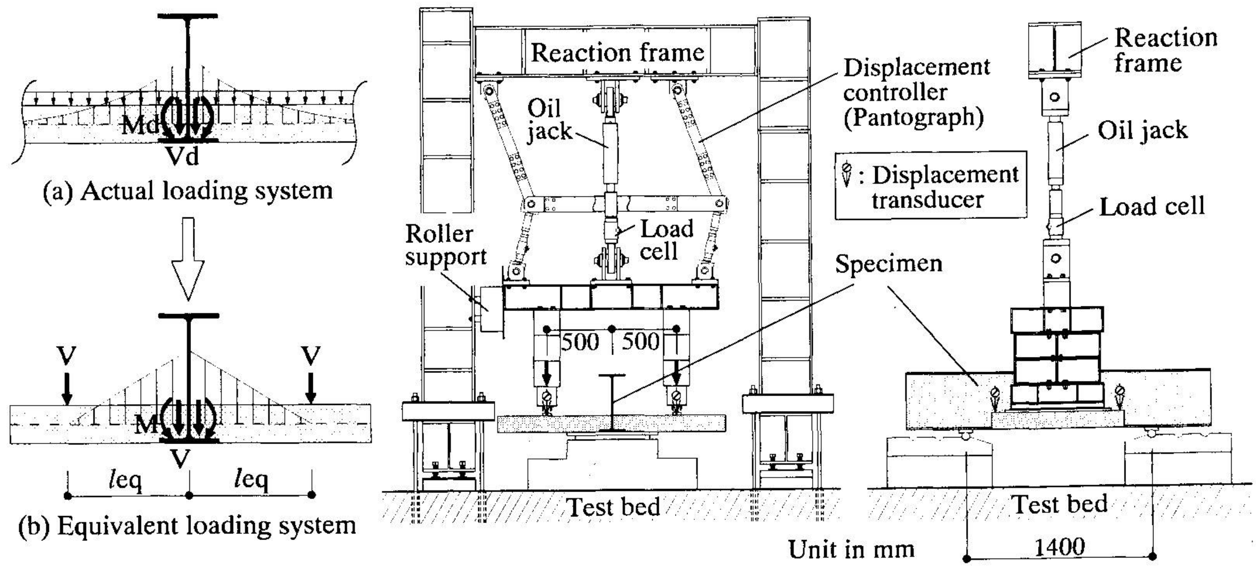



*Fig. 4 Test setup for inverted T-shape specimens*

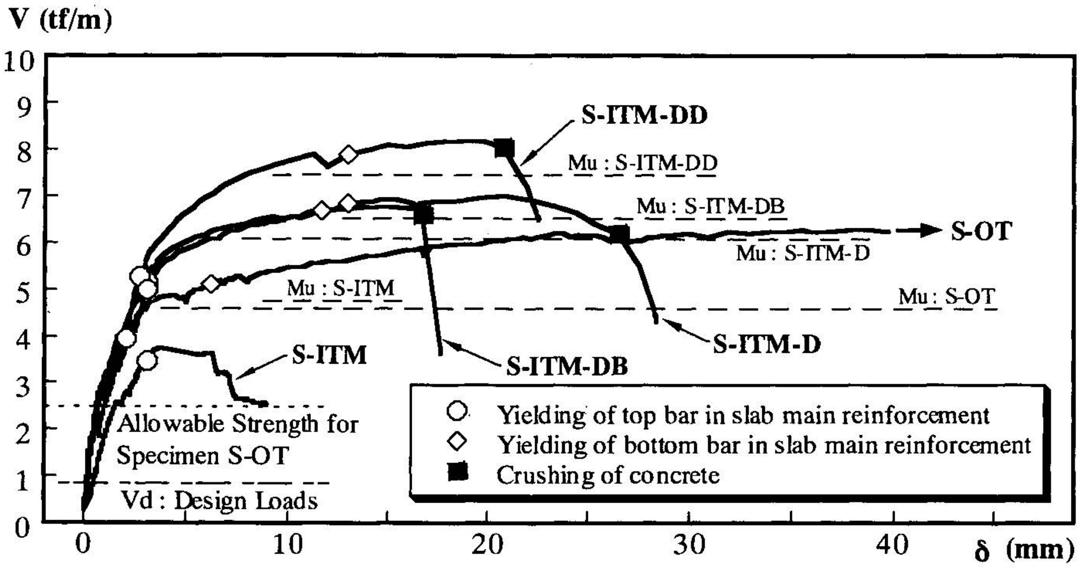
Illustrations (a) and (b) in Fig. 4 show the way how to determine this loading system. The illustration (a) is the actual bending moment diagram when the slabs are subjected to uniform distributed design dead plus live loads specified in the Building Code and Standard of Japan [4, 5], Md and Vd are the design bending moment and shear force at the fixed end of the slabs. While M and V as shown in illustration (b) are the bending moment and shear force at the fixed end of the slabs when the slabs of the specimens are respectively subjected to a concentrated load of V. In the present tests, application point of vertical loading (*l*eq) was determined so that ratio of the M/V would equal to the Md/Vd.

One displacement Controller (or Pantograph) as shown in Fig. 4 was installed in order to keep both of the vertical displacement at the left and the right loading points equal during the experiment.

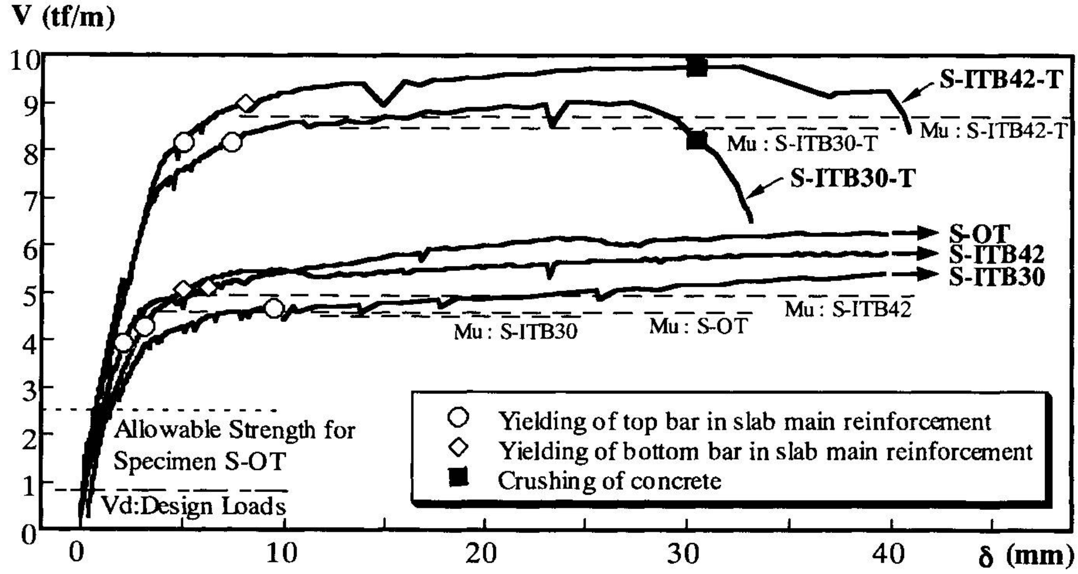
## 4. Test Results and Discussions

Applied vertical load (V) versus corresponding vertical displacement ($\delta$) relations obtained from the S-ITM Group and S-ITB Group specimens are shown in Figs. 5(a) and 5(b), respectively. (V)-($\delta$) relation of the specimen S-OT is presented in both Figs. 5(a) and 5(b) for comparison. In these figures, the vertical load (V) is the average of two measurements, and the vertical displacement ($\delta$) is the average of four measurements at the left and the right slabs. On each curve of the (V)-($\delta$) relations in Figs. 5(a) and 5(b), information obtained from the strain-gage measurements or visual observation is also marked using an open circle, an open square and a solid rectangle meaning respectively the initiations of tension-yielding in top and bottom bars for slab main reinforcement and crushing of the compression concrete at the fixed end of the floor slab. Also in each figure, the allowable strength for the ordinary T-shape specimen S-OT for long-term loading [4] and the ultimate strengths for all the specimens determined by a theory [4] are presented by dotted line and dashed lines, respectively. In addition, the design loads (Vd) based on the current Japanese Standards are also given in each figure. The theoretical strengths for all the specimens and ultimate strengths obtained from the experiment are presented in Table 2. Theoretical strengths for the specimens S-ITM-D, S-ITM-DD and S-ITM-DB presented in Fig. 5(a) and Table 2 are determined by the ultimate flexural strength taking into account the increase in flexural strength due to the contribution of special diagonal reinforcements.

The findings from the test results can be summarized as;
(1). The observed ultimate strengths (Vutest) of the test specimens except for S-ITM specimen are more than 6.7 to 11.7 times as large as the design load (Vd), and more than 1.6 to 2.5 times as large as the allowable strength for the long-term loading (Va).
(2). The ordinary T-shape specimen S-OT could develop its ultimate flexural moment capacity (Mu) and had excellent deformability without any concrete crushing.




*(a) S-ITM Group and S-OT specimens*




*(b) S-ITB Group and S-OT specimens*

*Fig. 5 Vertical load(V) versus displacement(δ) relations*

(3). For specimen S-ITM, which is an inverted T-shape specimen having the same slab reinforcing details as the ordinary T-shape Specimen S-OT, brittle shear failure occurred in a relatively small deformation area at the fixed ends of the R/C slabs as schematically shown in Fig. 6(a), and the ultimate flexural moment capacity could not be reached. This type of failure, which was also observed in the corresponding experimental specimens using R/C and SRC beams [1, 2, 3], could not be predicted by the existing design methods for ordinary T-shape R/C slabs as recommended by the current structural design standard in Japan [4].
(4). The special diagonal reinforcements, as provided in slab-to-beam connections of specimens S-ITM-D, S-ITM-DD and S-ITM-DB, could prevent the brittle shear failure as schematically shown in Fig. 6(b) and contributed to the increase in the ultimate flexural strength of the floor slabs.
(5). In the specimen S-ITM-DB, which is supplemented with the bottom reinforcements to slab-to-beam connection details adopted for specimen S-ITM-D, the crushing of compression concrete occurred in a smaller deformation area than that for the specimen S-ITM-D.
(6). Specimens S-ITB30 and S-ITB42 could develop their ultimate flexural moment capacities (Mu) and had excellent deformabilities without any concrete crushing.
(7). The supplemental top bars, as provided in specimens S-ITB30-T and S-ITB42-T, increased the ultimate strength of the floor slabs considerably.

*Table 2 Allowable strengths and ultimate strengths*

| Specimens | Theoretical Predictions | | | | Test Results |
|---|---|---|---|---|---|
| | Allowable Strengths for Long-term Loading | | Ultimate Strengths | | Ultimate Strengths |
| | Flexure : Ma* [tfm/m] | Shear : Va [tf/m] | Flexure : Mu* [tfm/m] | Shear : Vu [tf/m] | Shear : Vutest [tf/m] |
| S-OT | 1.00 | 2.51 | 1.83 | 4.58 | 6.28 |
| S-ITM | 1.11 | 2.78 | 1.90 | 4.75 | 3.74 |
| S-ITM-D | 1.70 | 4.24 | 2.81 (2.07 **) | 7.03 (6.08) | 6.98 |
| S-ITM-DD | | | 2.98 (2.94 **) | 7.45 (7.96) | 8.17 |
| S-ITM-DB | | | 3.05 (2.22 **) | 7.63 (6.52) | 6.92 |
| S-ITB30 | 1.09 | 2.73 | 1.80 | 4.51 | 5.57 |
| S-ITB42 | 1.11 | 2.78 | 1.98 | 4.95 | 5.86 |
| S-ITB30-T | 2.18 | 5.45 | 3.38 | 8.46 | 9.02 |
| S-ITB42-T | | | 3.49 | 8.73 | 9.77 |

* Bending moment at extreme-edge of bottom flange (E-E Section in Fig. 3)
** Values in parenthesis are bending moments at S-S Sections in Fig. 3.

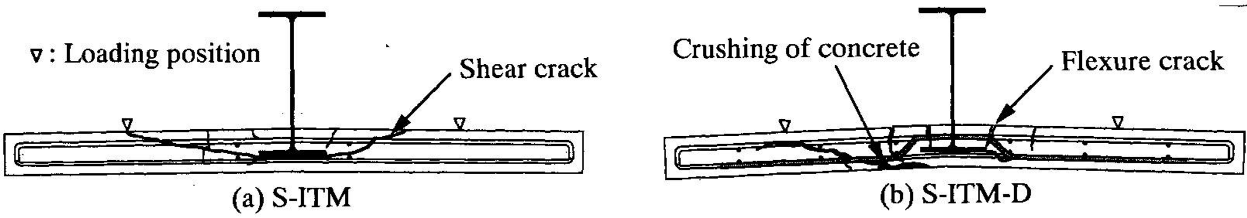



*Fig. 6 Typical crack patterns after test*

## 5. Concluding Remarks

In order to propose a better reinforcing method for R/C suspended slabs connected to the bottom flanges of steel H-shape beams, experimental study was conducted. Based on the obtained test results, it may be concluded that, in cases, where the bottom flange of the H-shape steel beam is located within the R/C suspended floor slabs, strength and deformation capacity of the inverted T-shape suspended slabs are very poor. However, it is possible to increase their ultimate strength and deformation capacity considerably by providing special diagonal reinforcing bars to the slab-to-beam connections. Also, when the bottom flange is located at the bottom surface of the R/C slabs, suspended slabs can develop their flexural moment capacities and excellent deformation capacities as good as the ordinary T-shape slabs. In addition, if supplemental top reinforcing bars are provided in the slab-to-beam connection, R/C suspended slabs can develop much higher strength.

## 6. References

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