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# DEVELOPMENT OF STIFFNER PLATE TIED STEEL COMPOSITE STRUCTURE
# PART2: STATIC SHEAR LOADING TESTS

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## ABSTRACT

The development of Steel Composite (SC) structures with enhanced impact resistance is crucial for nuclear facilities, particularly in the context of new regulatory standards in Japan concerning aircraft collision scenarios.

Continuing from Part 1 (Ishiki, 2025), which reported an overview of the design concept of the stiffener plate steel composite (SPSC) and basic test results, Part 2 focuses on experiments that investigate shear failure influenced by the fixation method of the surface steel plate, the connection method of the diaphragm plate, and the shear span ratio.

Through experimental studies, the effects of face plate anchorage, diaphragm plate connection method, and shear span ratio on shear capacity and stiffness were confirmed. The findings indicated that the anchorage mechanism of the surface steel plate significantly influenced structural behavior, particularly in terms of stiffness and load-bearing capacity. If the diaphragm plates are connected with sufficient strength, the effects of welding and bolting on stiffness and strength were minimal. Subsequent studies will verify impact resistance through dynamic tests.

## INTRODUCTION

With the implementation of new regulatory standards, operators of nuclear facilities must evaluate scenarios that exceed design basis events, such as aircraft collisions (APC). To mitigate the risks associated with top-heavy building designs that reduce seismic resistance, the development of rational structural thicknesses and innovative construction methods is imperative.

While current guidelines (JEA,2009) for SC structures do not mandate evaluations for out-of-plane shear performance against impact or impulsive load, concerns regarding shear-induced failure in short-span members and near member ends persist. It is hypothesized that the shear capacity of partition-type SC structures is greater than that of conventional tie-bar connected SC structures, which could provide a viable solution to this issue. Experimental validation is necessary to corroborate this hypothesis.

To deploy SPSC structures in practical applications, it is vital to assess their behavior under impact loads. However, there are constraints on the magnitude of impact loads that can be simulated in tests; consequently, scaled-down test specimens have been fabricated for performance confirmation.

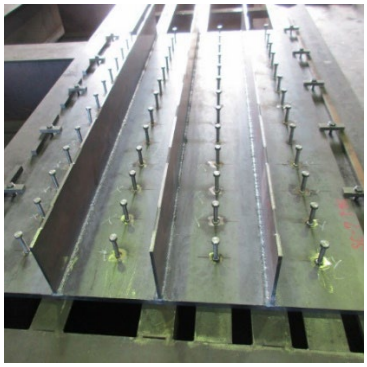
## EXPERIMENTAL CONDITION

### *Test Cases*

The test cases encompass several configurations, including different shear span ratios and connection types, such as welded and bolted connections. (Table 1, Figure 1)

Table 1: Test Matrix.

| Type | Anchorage | Connection | Depth d (mm) | Span 2a (a/d) | Material Prop. | Diameter/Pitch Plate thickness | Remarks |
|---|---|---|---|---|---|---|---|
| SC-7 | Stud Φ9@100mm | Stiffner plate Welded t6@200 w/hole | 500 | 1000 (1.0) | SS400 | Front (Compression) :6mm<br>Rear (Tension) :12mm | For Reference |
| SC-8 | Shear Connector L-30x30x5@100mm | | | | | | Proposed System |
| SC-9 | Stud Φ9@100mm | Stiffner plate Bolted t6@200 w/hole | | | | | |
| SC-10 | | Stiffner plate Welded t6@200 w/hole | | 1500 (1.5) | | | |



SC-07, SC-09, SC-10

SC-08

(a) Difference of Fixing Mechanism of Faceplate and Concrete.

SC-07, SC-08, SC-10

SC-09

(b) Difference of Connecting Mechanism of Stiffner plate.

Figure 1 Image of Difference of Each Test Specimen

***Test Specimen***

Figure 1shows an overview of the four types of specimens, with Table 2 and Table 3 detailing the properties of the materials used. SC-7 is the basic specimen of this test series, featuring a beam depth of 500 mm, a shear span ratio of 1.0, and studs used to anchor the surface steel plate. In SC-8, the fixation method is changed to an angle bar, while the basic specimen uses stud bolts. SC-9 is a test specimen in which the stiffner plate is connected by bolts, considering the actual construction method of the building. Finally, SC-10 is a test model with a shear span ratio of 1.5 for the basic case. The tensile steel plate of these 4 types of specimens was thickened to 16 mm to allow shear failure to occur first, with a shear span ratio of 1.0 used as the basis for the test.

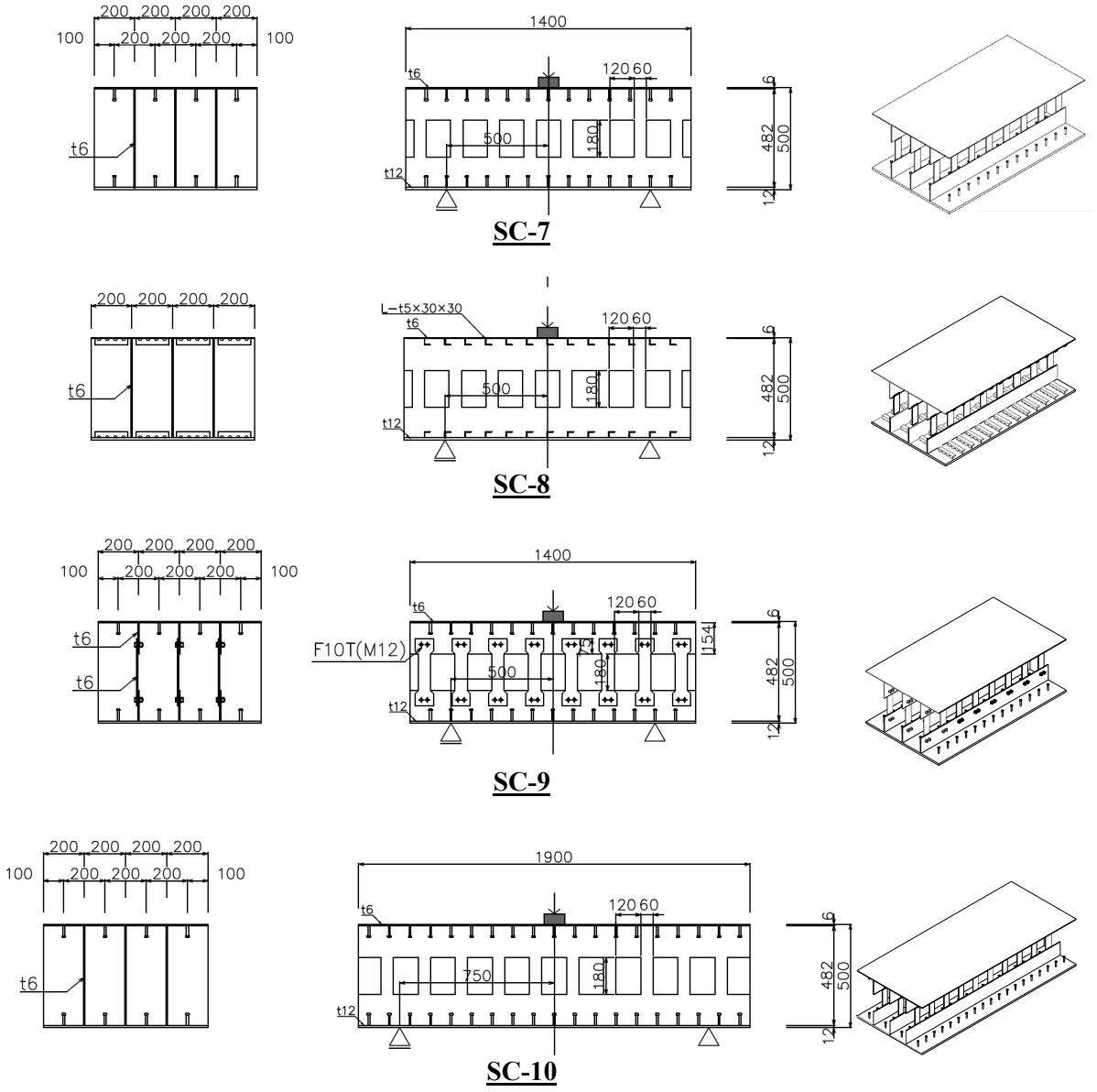



Figure 2. Test specimens for shear resistance tests.

Table 2: Material Properties of Concrete.

| Material | Compressive Strength (MPa) | Young's Modulus (GPa) | Poisson's ratio | Remarks |
|---|---|---|---|---|
| Concrete | 34.9 | 30 | 0.19 | 28 Days |

Table 3: Material Properties of Steel.

| Material | Type | Young's Modulus (GPa) | Yeilde Strength (MPa) | Tensile Strength (MPa) | Elongation (%) |
|---|---|---|---|---|---|
| Plate (SS400) | t=16 | 202.5 | 307.6 (Upper)<br>287.0 (Lower) | 435.0 | 31.5 |
| | t=6 | 197.4 | 395.2 (Upper)<br>377.0 (Lower) | 471.0 | 22.7 |
| Stud (SS400) | φ9 | 206.1 | 425.0 (Upper)<br>328.5 (Lower) | 494.0 | 33.0 |

***Load conditions and measurement plan***

Static loading tests were conducted on experimental SC specimens (SC-7 to SC-10) using a loading apparatus with a portal frame assembled on the test bed and a 10 MN structural testing machine. (Figure 3)

The loading method for all four specimens was three-point shear loading. The support jig and other fixtures used in the loading experiments were bolted to one of the 10 MN structure testers. Plaster was cast at the loading and support points of the pins and pin rollers on the top and bottom of the specimen to adjust for unevenness.

The loading of SC-8 commenced at a displacement control speed of 0.02 mm/s and continued at 0.04 mm/s near the maximum load. For the other specimens, loading was conducted at a load control rate of 2.0 kN/s from the initial stiffness to the vicinity of the inflection point, transitioning thereafter to a displacement control rate of 0.04 mm/s.

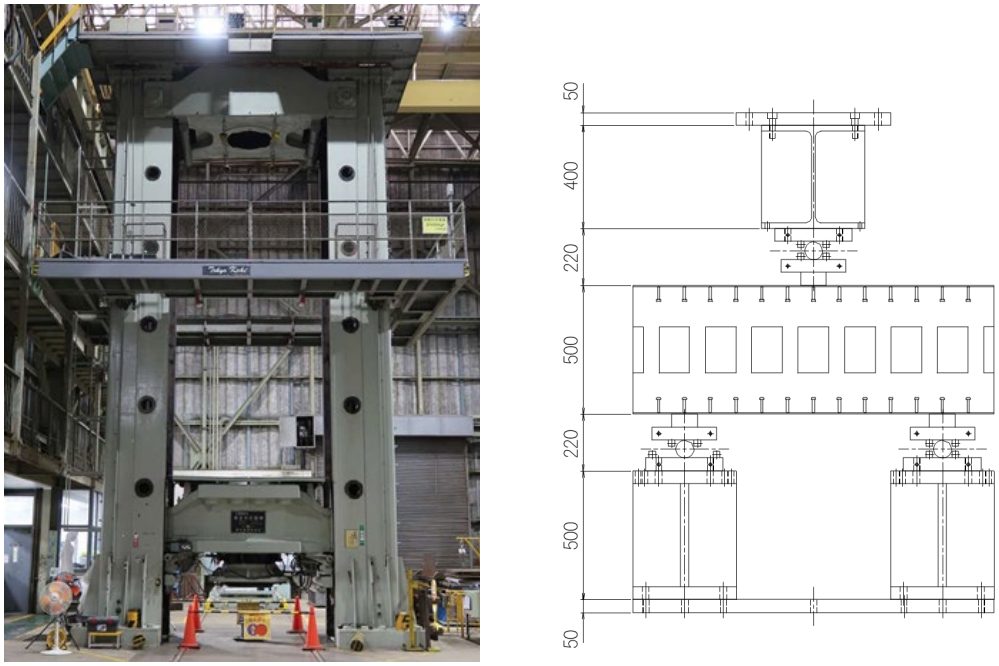



Figure 3: Test Apparatus

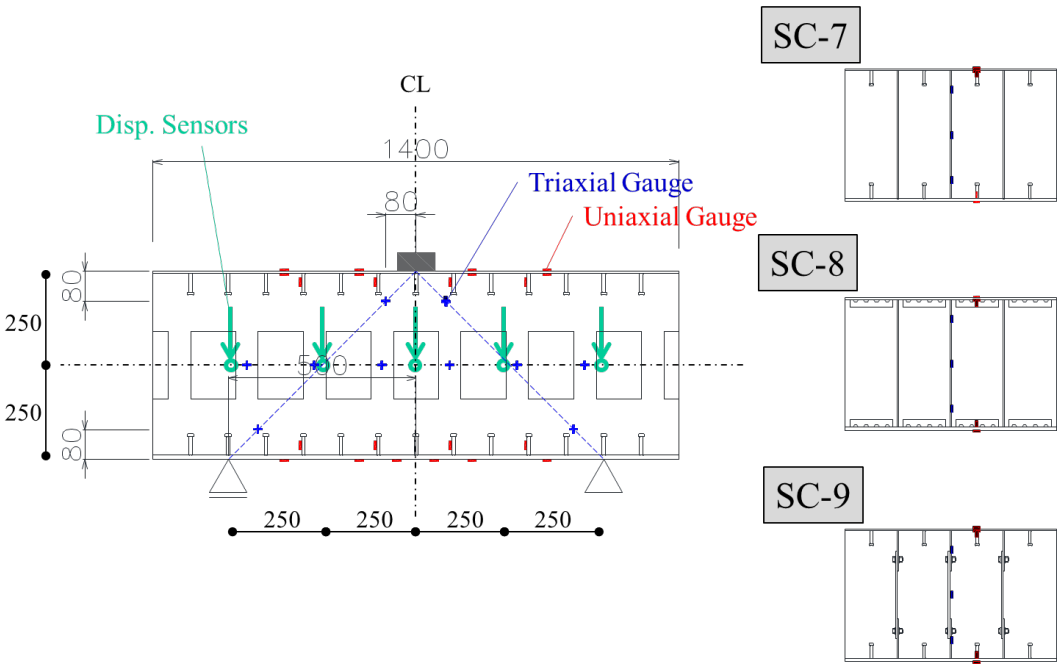



Figure 4: Measurement Plan

Table 4: Measuring Equipment List.

| Equipment | Type | Supplier | Quantity | 備考 |
|---|---|---|---|---|
| Static Measuring Instrument | TDS-540 | TML | 1 | |
| | TDS-530 | TML | 1 | |
| Switch Box | IHW-50G | TML | 2 | |
| Measurement Soft | TDS-7130 | TML | 1 | |
| Deformation Sensor | SDP-300D | TML | 1 | |
| | DTH-A-50 | Kyowa | 1 | |
| | SDP-200D | TML | 1 | |
| | CDP-100 | TML | Max.4 | |
| | CDP-50 | TML | Max. 4 | |
| | DP-500E | TML | 6 | Horizontal |
| | DP-500C | TML | 2 | For Pin-Roller Support |
| Load Cell | CLP-10MNS001 | TML | 1 | |
| | KCM-3MNAS | TML | 1 | |
| Strain Gauge | FLAB-3-11 | TML | 22 | SC-7,SC-8,SC-9 |
| | | TML | 22 | SC-10 |
| | FRAB-3-11 | TML | 10 | SC-7,SC-8,SC-9 |
| | | TML | 14 | SC-10 |

## RESULTS AND DISCUSSION

The load-deformation relationships from the SC-7 through SC-10 tests are shown and compared with Equation (1) (Arakawa, 1970), which estimates the average shear capacity of RC beams in Figure 5. Similarly, the load corresponding to the yield of the steel plate (2) on the tensile side is shown.

$$Q_{su} = \left\{ \frac{0.068 p_t{}^{0.23} (F_c + 18)}{M/(Q \cdot d) + 0.12} + 0.85 \sqrt{p_w \cdot \sigma_{wy}} \right\} b \cdot j \tag{1}$$

$$Q_y = at \cdot \sigma_y \cdot j \cdot 2/L \tag{2}$$

where,
- $p_t$ : Tensile Steel Ratio
- $F_c$ : Concrete Strength (N/mm$^2$)
- $M/(Q \cdot d)$ : Shear Span Ratio
- $p_w$ : Shear Rainforcement Ratio
- $\sigma_{wy}$ : Yield strength of shear reinforcement (N/mm$^2$)
- $b$ : Beam Width (mm)
- $j$ : Distance between centers of stress (mm)
- $at$ : Cross Section Area of Tensile Steel (mm$^2$)
- $\sigma_y$ : Yield strength of faceplate (N/mm$^2$)
- $L$ : Support Span (mm)

From the photographs, cracks indicative of shear failures in the concrete sections can be observed in all cases. The load-deformation relationships demonstrate that in all instances, the shear capacity exceeds the average shear capacity of the RC beams with equivalent reinforcement ratios, with specimens showing higher ductility compared to traditional RC beam shear failures. The maximum capacity of SC-7, SC-9, and SC-10 corresponds clearly to the yielding of the surface steel plate, suggesting that as long as the surface steel plate restrains the concrete, it can transmit out-of-plane shear forces. Notably, in SC-7, SC-9, and SC-10, the onset of stiffness reduction in the load-deformation relationship occurs from loads exceeding the shear strength level, similar to RC beams, indicating that the shear failure of the internal concrete affects the out-of-plane stiffness of the members.

Conversely, SC-8 displays a different trend, lacking the stiffness reduction observed at the shear failure level of the concrete section, with maximum bearing capacity surpassing the plasticization level of the surface steel plate. Additionally, SC-8 does not exhibit the stiffening behavior seen in the other specimens, where stiffening occurs before reaching maximum proof stress.

Figure 6 to Figure 8 illustrate comparisons of each test against SC-7. SC-8 is characterized by the absence of stiffness reduction at the shear failure level of the concrete section and the increase in bearing capacity as described. It is assumed that the difference in the anchorage mechanism causes variations in central displacement due to changes in the ratio of shear deformation and bending deformation, as well as the stiffening effect against local buckling. However, further experimental or numerical analysis is needed for verification. The load-deformation relationship for SC-9 closely aligns with that of SC-7, suggesting that changes in the stiffner plate connection method have minimal impact on stiffness and bearing capacity. Although differences in behavior post-maximum bearing capacity exist, they may be attributed to individual variances. For SC-10, the dashed line indicates results that correct the deformation by the coefficient of bending deformation of SC-10 for the span ratio, revealing that the damage process is fundamentally similar across cases with varying shear span ratio and also suggests that the contribution of bending deformation is significant even at this short span.

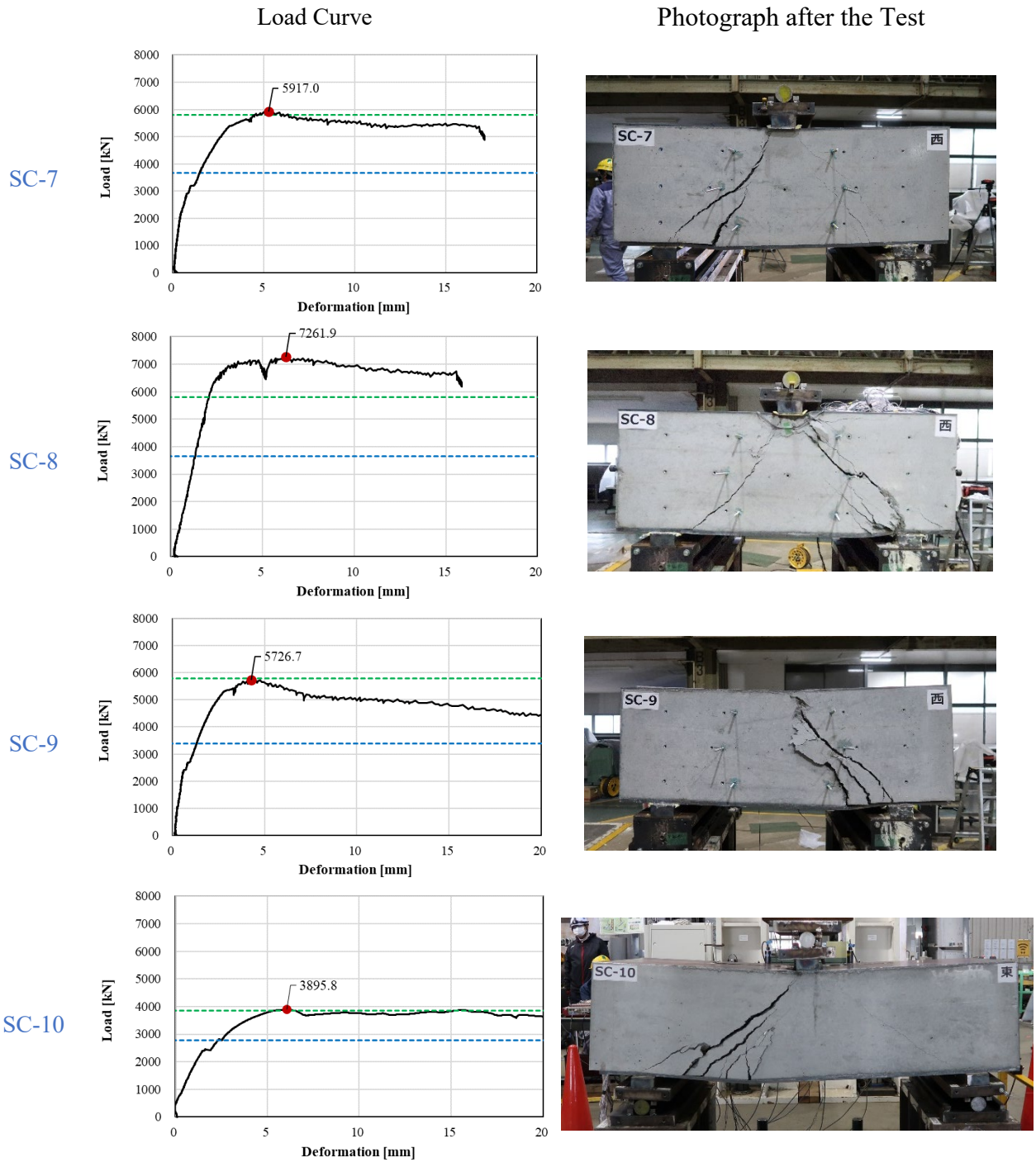



Figure 5: Photographs after the test and load-deformation relationship.

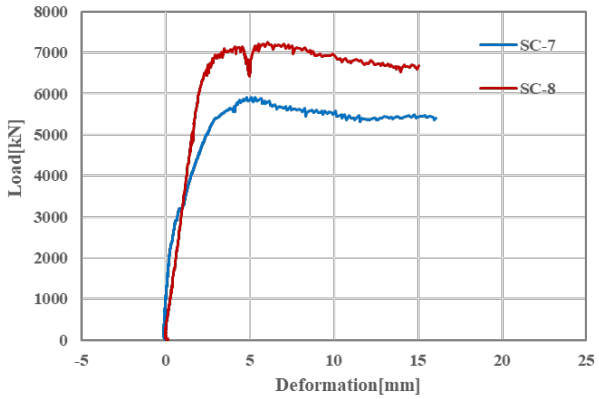



Figure 6: Comparison of SC-7 and SC-8

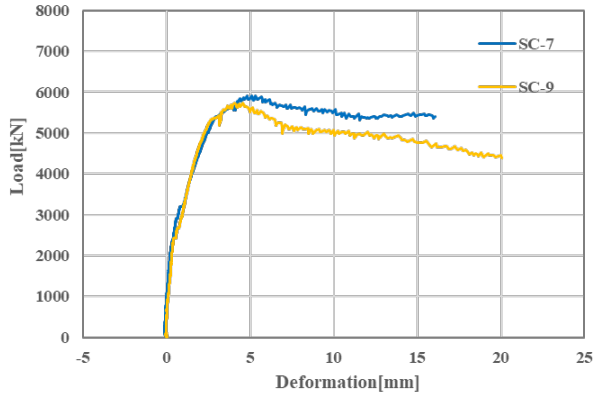



Figure 7: Comparison of SC-7 and SC-9

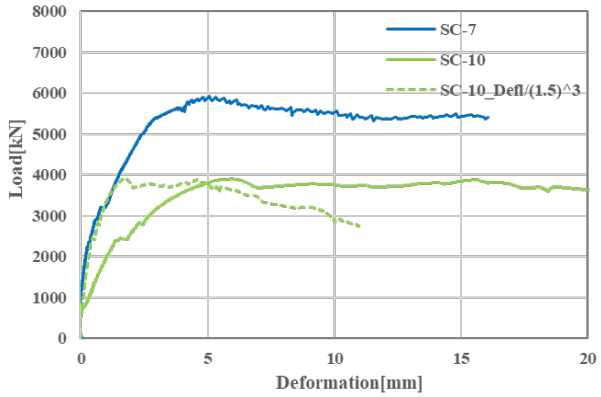



Figure 8: Comparison of SC-7 and SC-10

## CONCLUSION

The experimental investigations demonstrated that the shear capacity and stiffness of the tested SC structures (SC-7, SC-8, SC-9, and SC-10) exceeded that of traditional reinforced concrete beams with similar reinforcement ratios. Notably, the results indicated that the anchorage mechanism of the surface steel plate significantly influenced the structural behavior, particularly in terms of stiffness and load-bearing capacity and if the diaphragm plates were connected with sufficient strength, the effect of welding and bolting on stiffness and strength was small. The study confirmed the hypothesis that SPSC structures could offer improved shear capacity compared to traditional tie-bar SC structures, thereby providing a potential solution to mitigate shear-induced failures.

The results will be instrumental in evaluating the out-of-plane shear performance of SPSC structures and will guide future design systems aimed at enhancing impact resistance, particularly in nuclear facility applications.

## REFERENCES

Arakawa, T. (1970), "Allowable shear stress and shear reinforcing in reinforced concrete beams," Journal of JCI, Vol.8, No.7

Ishiki K. (2025), “Development of diaphragm plate tied steel composite structure part 1: Static Flexural Loading Tests”, Proceedings of 28th International Conference on Structural Mechanics in Reactor Technology (SMiRT28), Toronto, Canada.

Japan Electric Association. (2009). *JEAC 4618-2009 Technical Code for Seismic Design of Steel Plate Reinforced Concrete Structures*. Tokyo, Japan.