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DEVELOPMENT OF STIFFENER PLATE TIED STEEL COMPOSITE STRUCTURE PART3: PREPARATION OF DYNAMIC 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) and Part 2 (Yabuuchi, 2025), which reported an overview of the design concept of the stiffener plate steel composite (SPSC) and structural test results, Part 3 focuses on the outline of the impact resistance performance test plan and each preparatory test. First, we presented the policy for the test specimen design and demonstration tests. And then, the design and verification tests of a projectile to simply simulate the impact loads of a commercial aircraft, for use in subsequent dynamic tests.

INTRODUCTION

With the introduction of new regulatory standards, operators of nuclear facilities are required to assess scenarios that go beyond design basis events, such as aircraft collisions (APC). On the other hand, to reduce the risks associated with top-heavy building designs that compromise seismic resistance, it is crucial to develop rational structural thicknesses and innovative construction techniques.

Although existing guidelines for SC structures do not requires evaluations of out-of-plane impulsive and impactive loads, concerns regarding shear-induced failures in short-span members and near the ends of members continue to exist. It is suggested that the shear capacity of SPSC structures is higher than that of conventional tie-bar SC structures, potentially offering a feasible solution to this problem. Experimental validation is essential to support this hypothesis.

To implement SPSC structures in practical applications, it is critical to evaluate their behavior under impact loads. However, there are limitations on the magnitude of impact loads that can be simulated in tests, leading to the creation of scaled-down test specimens for performance validation.

In Part 1 and Part 2, the authors presented an overview and the results of basic static tests to confirm the ability of the SPSC to withstand out-of-plane loads and its fracture characteristics, and in Part 3, we will discuss the manufacturability of the specimen during scale-down and the design of the specimen and flying object in preparation for the subsequent dynamic tests.

DESIGN OF TEST SPECIMEN

Scaling Law

The impact tests were planned with scaled structures and projectiles, following a scale ratio of 10 for overall sizing, where the static tests were performed according to the 1/5 scaling law. Scale laws for each parameter in the dynamic test are shown in Table 1. The velocity and stress remain consistent with real scale conditions, simplifying the interpretation of test results. Additionally, the density matches that of the real scale, aiding in the construction of scaled reinforced concrete structures.

Table 1: Scaling Law.

Physical quantity	Scale factor
Length	$1/\lambda$
Stress	1
Density	1
Acceleration	λ
Time	$1/\lambda$
Mass	$1/\lambda^3$
Frequency	λ
Displacement	$1/\lambda$
Velocity	1

Specimen Design and Verification Test

Figure 1 shows an overview of the test specimens. This is the basic specimen of this test series, featuring a beam depth of 250 mm, a shear span ratio of 2.4, and studs used to anchor the surface steel plate. The scale ratio was changed for the static tests reported in Part 1 and Part 2. In addition, the width of the specimen was tripled compared to the static test specimen to account for the spread of the load during impact. In addition, the surface steel plate was modified to be a closed type to resist momentary slippage of the surface steel plate.

Verification tests were conducted to determine the effect of lowering the scale ratio. An overview of the static tests is shown in Figure 2, and a dimensionless comparison of the load-deformation relationships among the test results is shown in Figure 3. The results show that the behavior up to yielding is generally consistent. The higher yield load in the scaled specimen was attributed to the fact that the yield strength of the thin steel plate was about 470 MPa, while the strength of the 1/5-scale specimen was about 420 MPa.

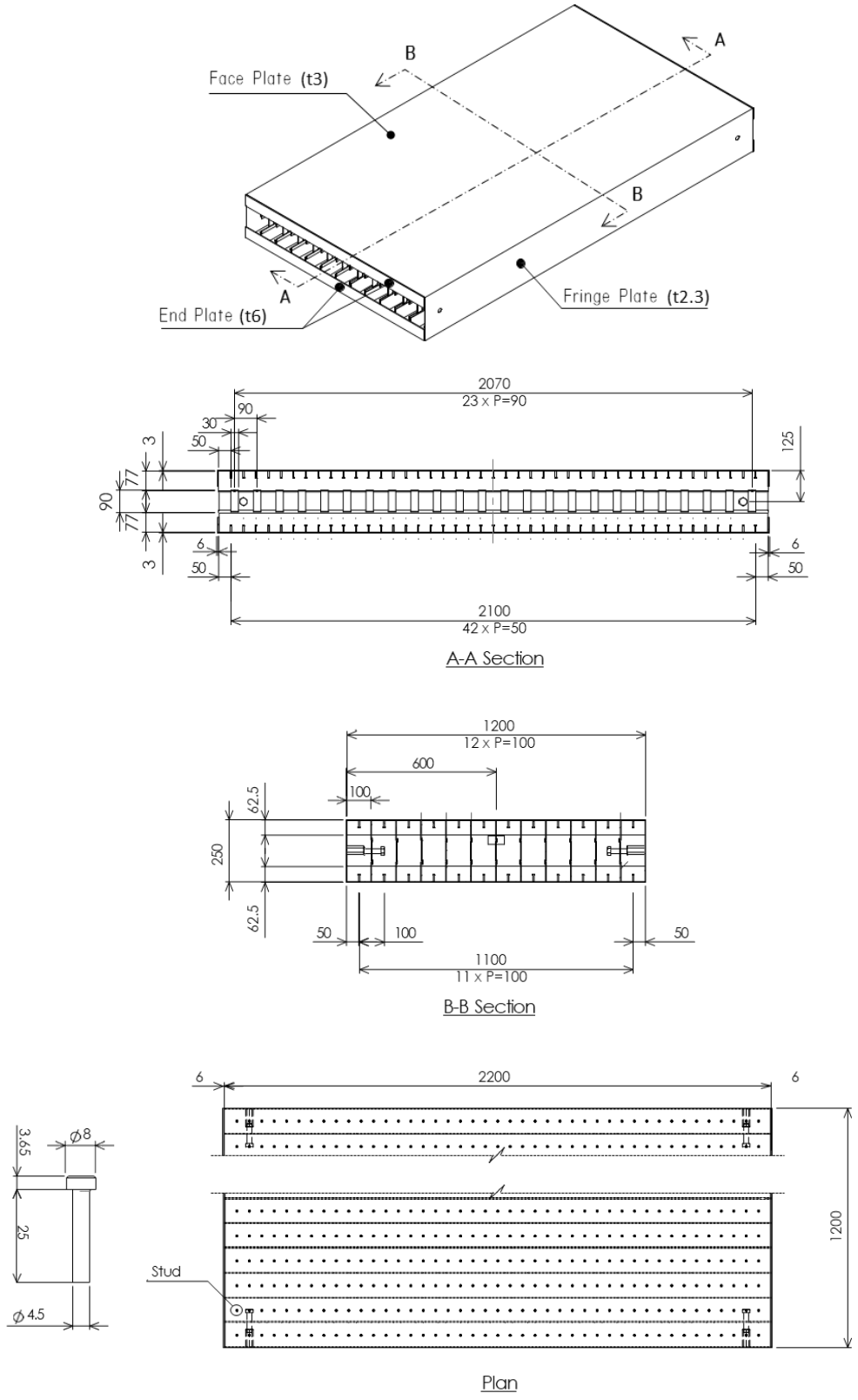
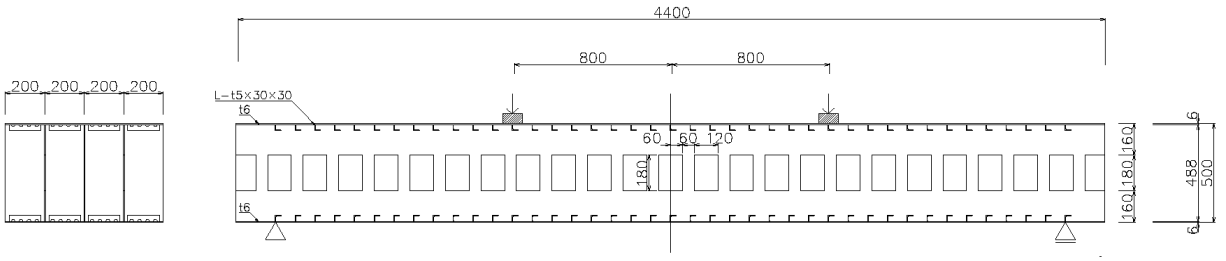
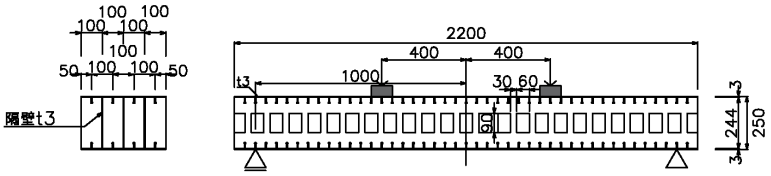


Figure 1. Test specimens for dynamic tests.

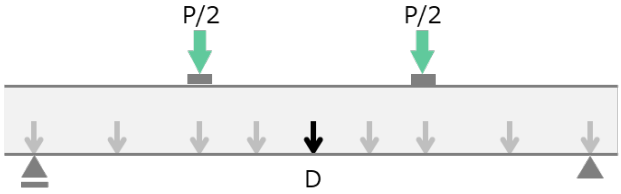


(SC-5: 1/5 Scale)



(SC-11: 1/10 Scale)

Figure 2: An overview of the static tests



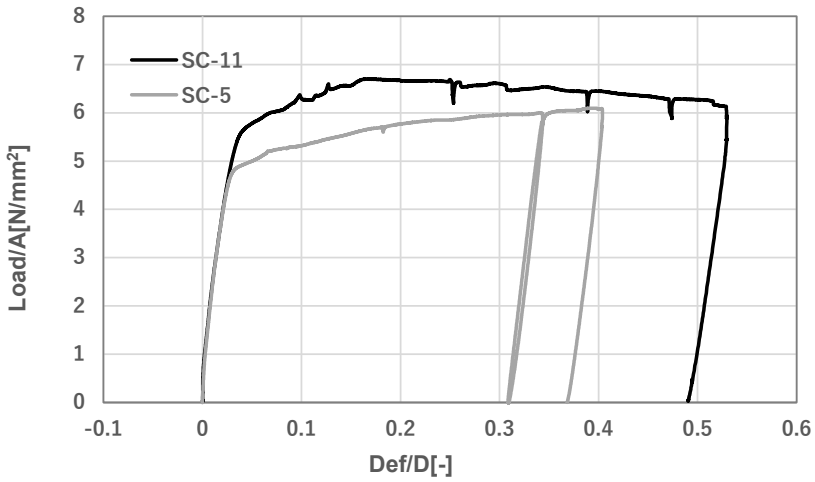


Figure 3: Comparison of Stress-Strain relationships in Verification Test

DESIGN OF PROJECTILE

Simplification of Aircraft Impact Loads

The concept for simulating the impact of a commercial aircraft with scale-reduced loads is shown in Figure 4. First, a aircraft which has a total weight of 250 tons and a total length of 64 m was assumed from the literature. Then, the aircraft was divided into three stages ("nose," "wings," and "tail"), and a rectangular or triangular distribution was assumed since the impact load of a soft-flying aircraft is proportional to the mass per unit length according to Riera's concept (Riera, 1982). Finally, based on the use of market products, a basic plan for the projectile was formulated assuming the use of a 318 mm diameter stainless steel pipe and the weight of the tail, which cannot be taken into account due to the limitations of the test apparatus, is allocated to the front half.

Here, the following two points should be noted with respect to the diameter being smaller than it actually is. First, the buckling strength of the projectile increases relative to the ideal scaled-down diameter, causing deceleration during impact, and the load due to the mass of the heavy section, especially in the latter half of the impact, may not be given as expected. Second, the load area will be smaller than the ideal load, making the loading conditions more severe than in reality. A larger number of diaphragm plates placed in the load area would be expected to improve the load transfer capability, but since the same load is applied in a smaller load area, the test will be conducted under conditions where punching fractures, which are unlikely to occur in reality, are more probable.

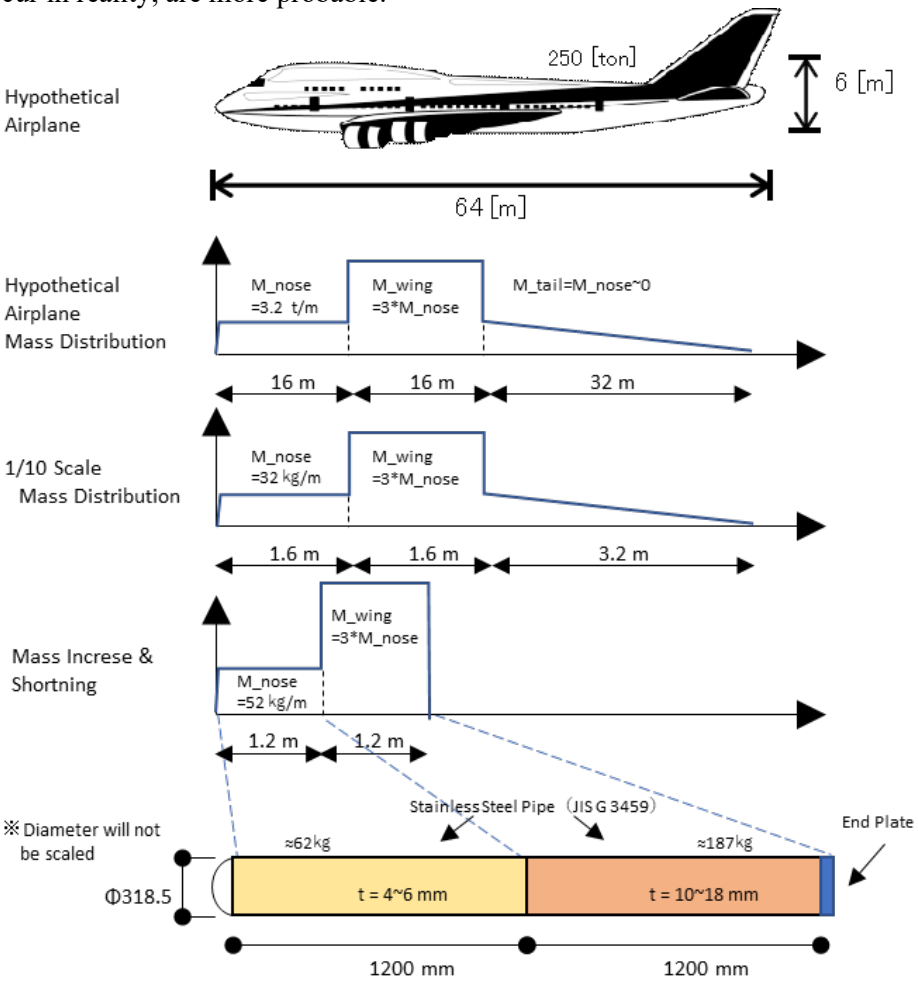


Figure 4: The concept for simulating the impact of a commercial aircraft

Design of Projectile

As mentioned in the previous section, the ideal load given by a mass with infinitely small strength and little deceleration, whereas the phenomenon on the target includes the effect of the load given by the destruction of the projectile and the deceleration of the projectile itself. Figure 5 shows two plans for the design of a flying object that has been subjected to a large amount of elastoplastic numerical analysis and has shown good response to the target load (Figure 6). The front half is made of thin steel plates and holes are drilled to reduce the fracture strength of the projectile and the tail section is composed of a thick steel pipe and a bottom plate, assuming that the tail section will not be destroyed, and considering the acceleration method used during the test. The load at impact for both designs is shown overlaid with the target load.

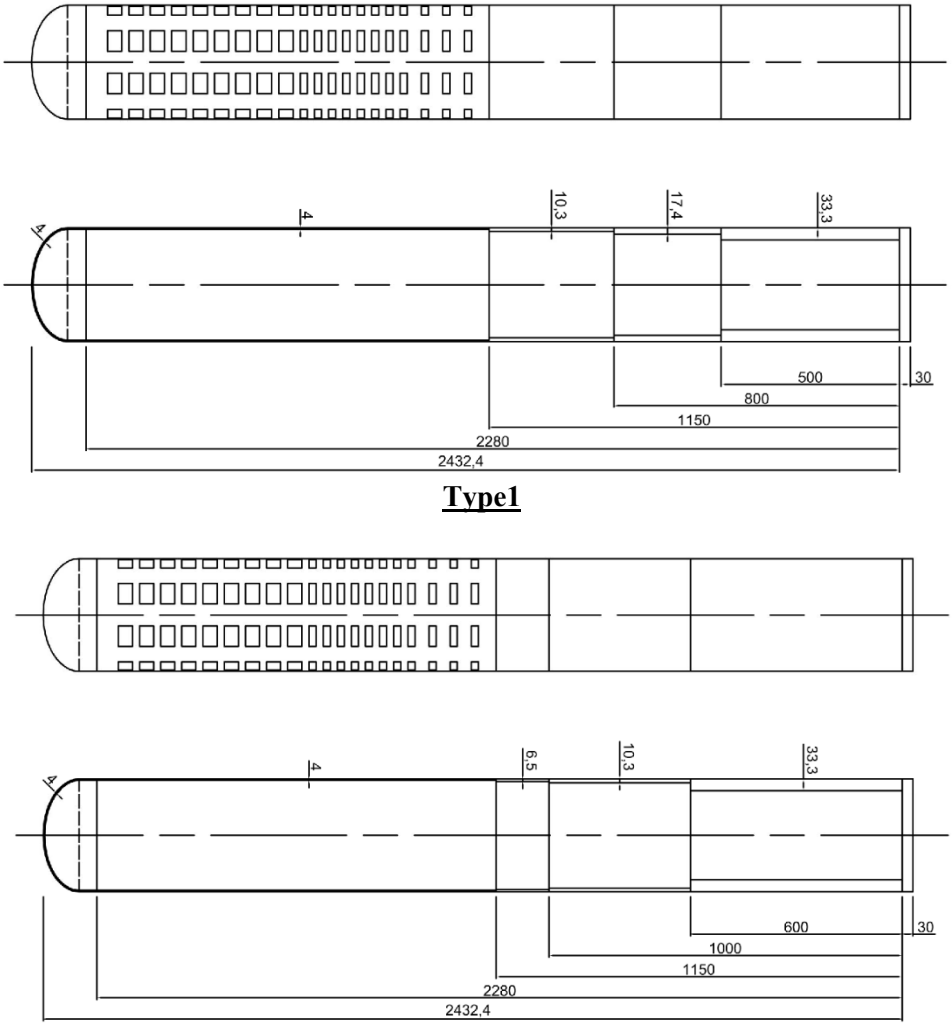


Figure 5: Projectiles (Type 1 & Type 2)

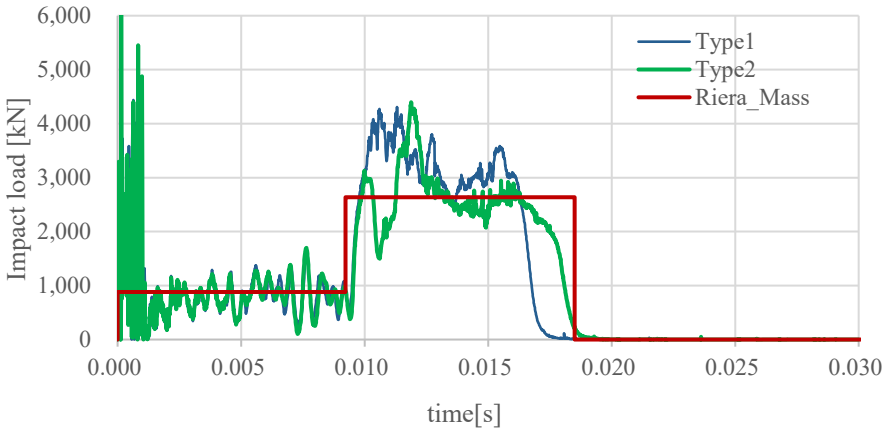


Figure 6: Numerical simulation vs Riera curve (Only Mass Distribution)

Verification Test

Actual fabrication (see Figure 7) and rigid-plate tests were conducted on the Type 1 and Type 2 projectiles. Table 2 lists the test cases and actual measured values of impact velocity, Figure 8 shows the test records from the high-speed camera, Figure 9 shows the projectile after the test, and Figure 10 shows the load-deformation relationship compared to the Riera load for each velocity.
SCFP-1 achieved the expected two-step loading, albeit at a lower level than the target load due to the lower-than-expected impact velocity; SCFP-2 did not have a sufficient rise in load around 0.01 seconds and showed a large peak around 0.02 seconds. SCFP-3 and SCFP-4 achieved a load curve close to the expected one.

The results confirm the effectiveness of both types. However, there was one case in which type 2 exhibited a failure or load different from that assumed, so it was decided to conduct this test using type 1.

Table 2: Test Matrix.

Test id	Missile Type	Missile mass (kg)	Impact velocity (m/s)	Impact duration (ms)
SCFP1	1	226.7	114.2	20.7
SCFP2	2	225.7	123.6	18.4
SCFP3	1	226.7	126.6	17.3
SCFP4	2	225.7	130.4	17.7

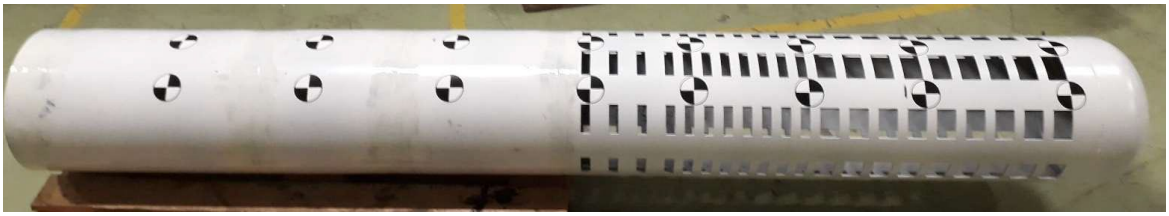


Figure 7 Fabrication of projectile

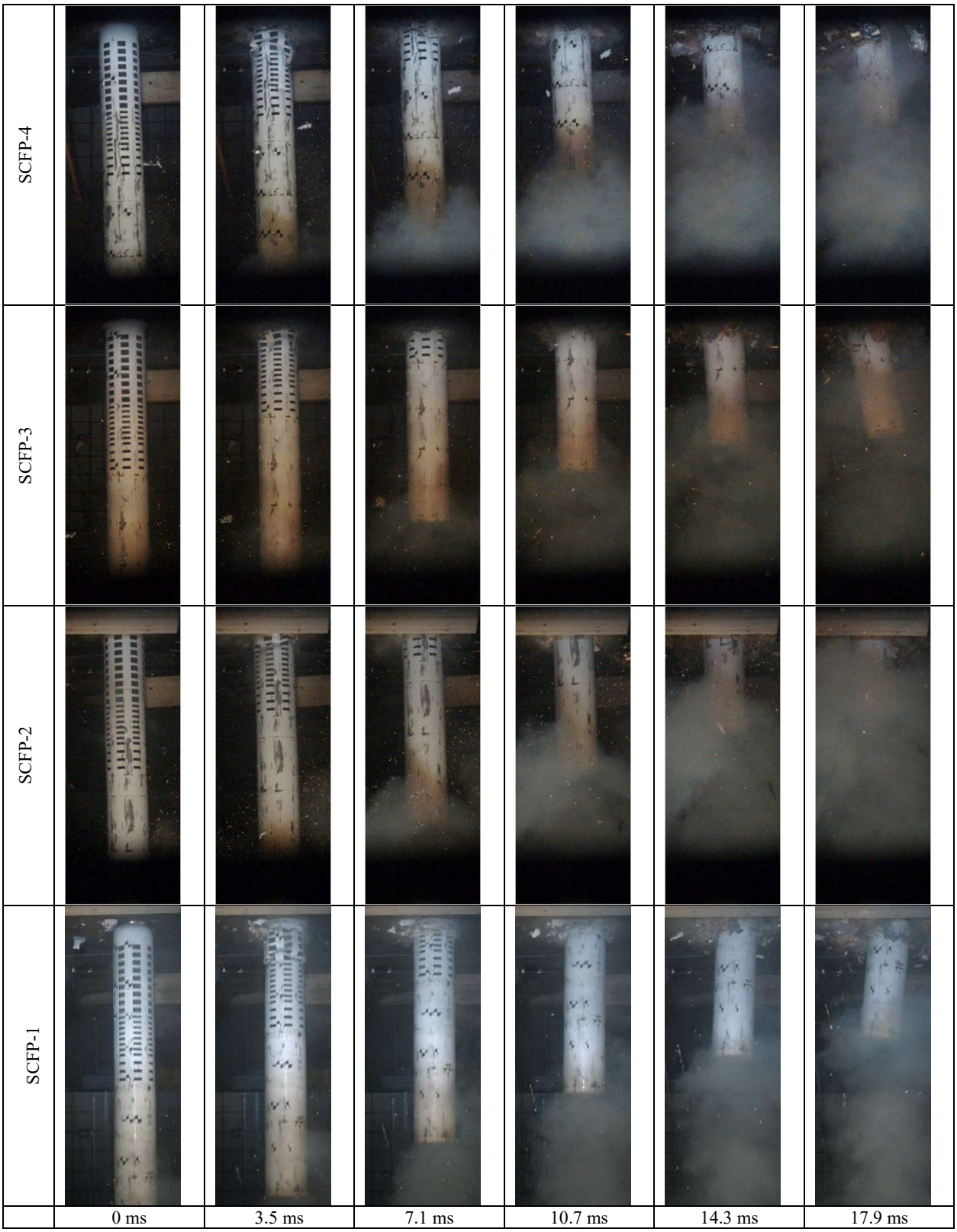


Figure 8: Still pictures from the high shutter speed video

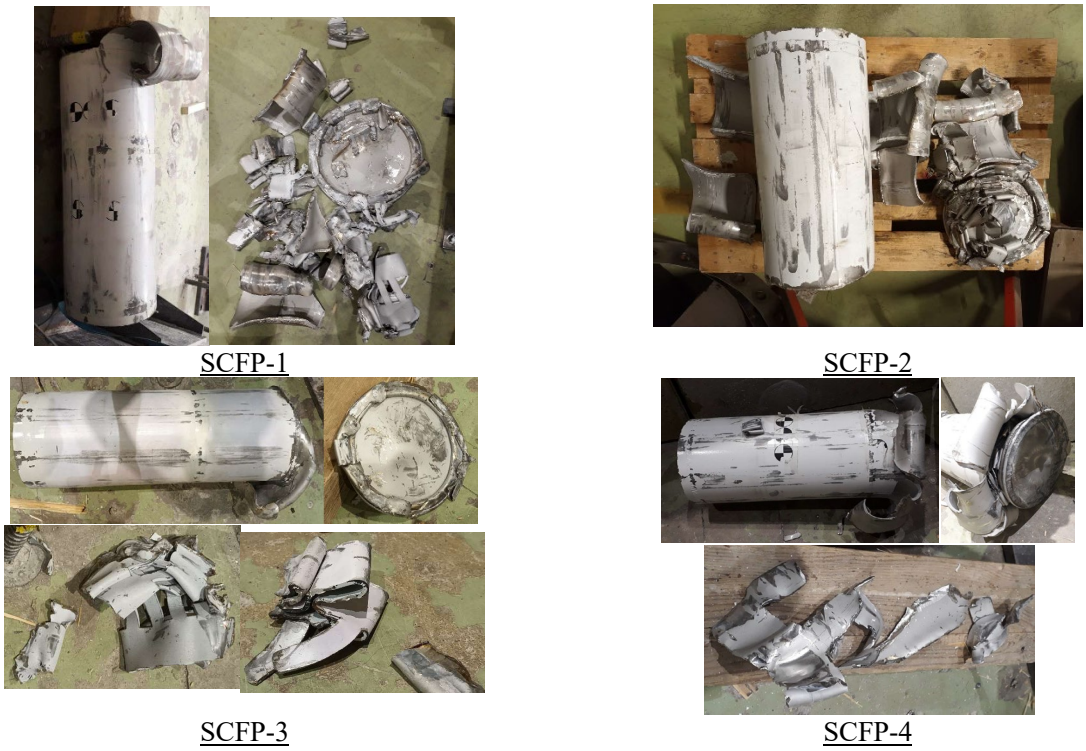


Figure 9: Photographs after the test.

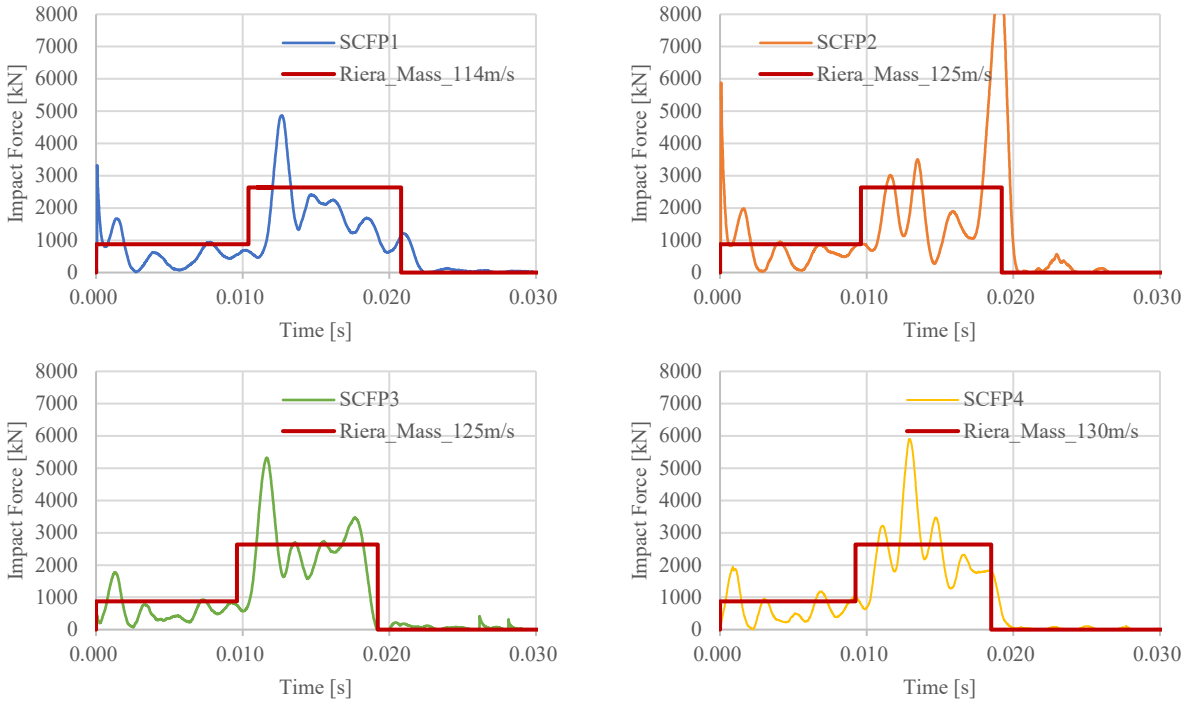


Figure 10: Load-deformation relationship vs Liera curve (Mass Distribution).

CONCLUSION

In Part 3, we presented the policy for test specimen design and demonstration tests, as well as the design and verification tests of a projectile to simply simulate the impact loads of a commercial aircraft, for use in subsequent dynamic tests.

In the design of the test specimen, static loading tests were conducted on the specimen, which was scaled down to 1/10, and it was confirmed that the behavior of the test specimen was almost equivalent to that of the original model which was a 1/5 scale model.

Regarding the design of the projectile, the two designs were fabricated, rigid wall tests were conducted, and their usefulness was verified. The results of the tests showed that the Type 1 projectile was the more stable of the two proposals, and we decided to use the Type 1 projectile in the following impact tests.

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