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TECHNICAL CONCEPT AND FEASIBILITY OF STEEL SHEET REINFORCED SYNTHETIC WOOD BEAM

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ABSTRACT: This paper is intended to explain the technical concept of steel sheet reinforced synthetic wood (SSRW). SSRW focuses on improving the integrity of wood and steel to increase the strength and toughness of hybrid materials. The composition includes laminated wood inserted with thin steel sheets prepared with adhesive holes and dowels. We conducted scale-model experiments to evaluate the feasibility of SSRW. We found that the vertical insertion of steel sheets demonstrated notable gains in rigidity and strength. Further, we observed that SSRW achieves 1.9 to 2.1 times greater bending rigidity as well as gains in strength than the unreinforced specimen.

KEYWORDS: Laminated wood, Adhesive opening, perforated steel metal

1 INTRODUCTION

Steel sheet reinforced synthetic wood (SSRW) is a wood-steel-hybrid-material for structural members, with a steel sheet reinforcement inserted in the cross-section of synthetic wood, as shown in Figure 1.
The purpose of SSRW is to compensate for the discontinuity of potential defects. Inserting the steel sheets between adhesive surfaces of wood can mitigate inconsistency in material strength.
In addition, this can moderate the localized stress concentration at the joint, which tends to be a critical part of structure design.

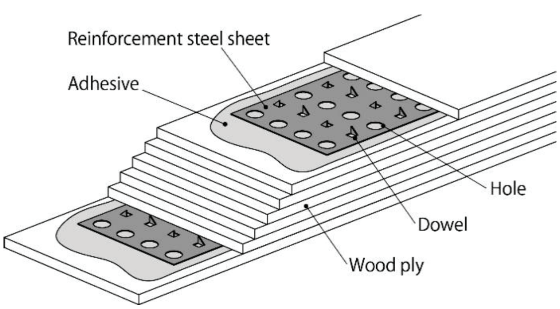

Figure 1: *Composition of SSRW*

Figure 1 shows the composition of SSRW.
Thin steel sheets are inserted and sandwiched between the adhesive layer of engineering wood.
The steel sheet has holes through which the adhesive penetrates and dowels that bite into the wood for temporary mechanical fixing and alignment.

2 PREVIOUS INVESITIGATIONS

Here, we discuss two recently proposed wood-steel hybrid beams.
Tanaka et al. (2007) prepared synthetic wood specimens with a 200 mm × 100 mm cross-section and added 6 mm-steel plates.
There were two specimens: plates on the bottom sides only, and on both the top and bottom. This was done using lag screws without adhesive.
They conducted a 3-point bending test with a span of 4 m and found that in both specimens, the maximum strength was approximately 1.2 times greater than that of plain wood.
The fracture behaviour of the specimens showed cracks in the wood material stressed by lag screws.
This is significant, especially on the tension side (bottom), where the wood was separated with a gap because the stretch of wood material could not follow that of the steel plate.
Winter et al. (2012) prepared 360 mm × 160 mm cross-section of synthetic wood inserted with cold formed or welded H shaped 4 mm-thick steel plate in wood material grooves by four threaded rods.
They conducted 4-point bending tests with a span of 6 m and found that the maximum loads of cold-formed and welded sheets were similar.
The fracture behaviour of both specimens was wood material rupture on the tension side.
This fracture occurred because the wood material could not follow the bending of the steel plate inside the beam.
These previous investigations were generally aimed at achieving high rigidity and high strength in hybrid beams.
The hybrid material was wood with thick steel plates, which had low integrity.

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Additionally, beam fractures were caused by the rupture of the wood on the tension side of the hybrid material.
In SSRW, a very thin steel sheet is used as the reinforcing material to obtain uniform rigidity with wood.
We focused on improving the cross-sectional integrity and bending performance of wood material and steel plates.
This hybrid beam aims to improve toughness rather than rigidity.

3 EXPERIMENT OUTLINE

We conducted 3-point and 4-point bending tests in three phases. The bending tests were performed until the specimen fractured.
A scale-model was used for the specimens to comprehensively study many experimental parameters in a short time and at a low cost.
We observed the maximum proof strength, initial rigidity and fracture behaviour in the bending tests.

3.1 TEST SETTING

1) Phase 1 and Phase 2
Phase1 and 2 were 3-point bending tests.
The span of each specimen was 600 mm.
Figure 2 shows the test setting.

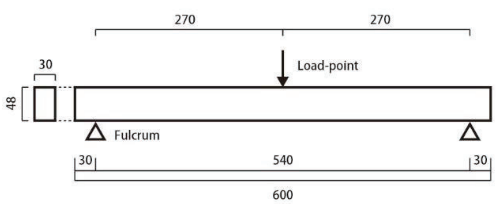

Figure 2: *Test setting in phase 1 and phase 2*

2) Phase 3
Phase 3 consisted of 4-point bending tests.
The span of the specimen was the same as that used in the previous phase.
Figure 3 shows the test setting in phase 3.

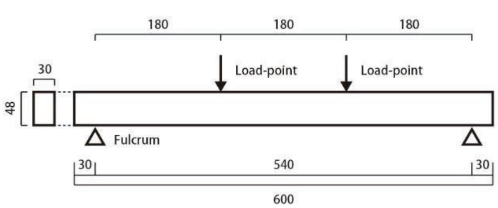

Figure 3: *Test setting in phase 3*

3.2 SPECIMEN PREPARATION

Figure 4 shows the specimen production process.
The specimens were 30 mm × 48 mm in cross-section and 600 mm in length and were made of 6 mm thick falcata laminated wood bonded with an epoxy resin adhesive.
Galvalume steel sheets 0.27 mm thick were used as the reinforced steel sheets.

The test specimen fabrication method:
(a) Markings were made directly on the steel sheet where the hole was drilled.
(b) Steel sheets of 0.27 mm thick were cut to 680 mm × 36 mm size.
(c) Holes were punched along the markings.
(d) The holes and cutting edges of the steel sheet were planar compensated using a plastic hammer.
(e) The surface of the steel sheet was degreased with ethanol.
(f) Steel sheets were placed along the markings of the lamina, and the lamina and buck sheets were laminated.
(g) The specimen was temporally fixed with a clamp.

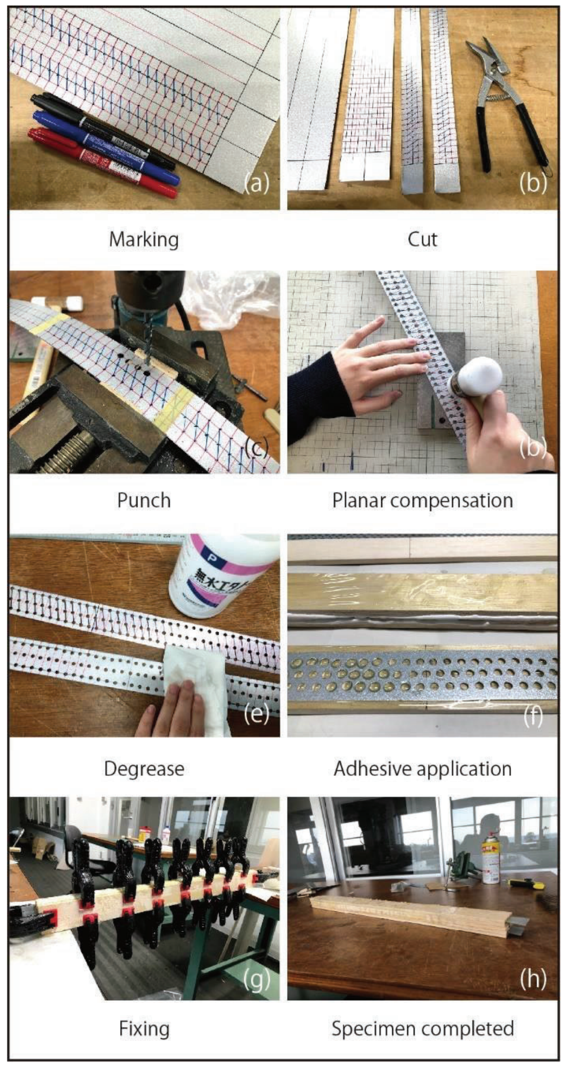

Figure 4: Specimen preparation

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4 EXPERIMENTS

The experiment was conducted in three phases.

4.1 [PHASE 1]: EFFECT OF INSERTION DIRECTION

In phase 1, specimens with steel sheets inserted vertically and horizontally were prepared, as shown in Figure 5 and 7.

The main parameter of phase 1 was the cross-sectional insertion direction to confirm its effect on the performance of the specimen.

The parameter was also prepared to examine the effect of dowels.

1) Specimen parameters

In phase1, we used 7 specimen types.

One laminated wood beam with only lamina stacked vertically in cross-section was prepared.

Three specimens were prepared with steel sheets inserted vertically, and three specimens were prepared with steel sheets inserted horizontally.

2) Results: Load-deflection relationship

Figure 6 shows the load deflection relationship in the vertical insertion group.

This group of specimens significantly outperformed the unreinforced specimens in terms of initial rigidity and maximum proof strength in all the tests.

The initial rigidity was 1.9 to 2.1 times higher, and the maximum proof strength was 1.3 to 1.5 times higher.

The V-N specimens exhibited the highest initial rigidity, but the lowest maximum proof strength.

The lack of holes in the steel sheets caused premature delamination of the lamina and steel sheets.

V-4Hm-3.3 with holes showed the greatest maximum proof strength.

V-3Dm-4 with dowels applied to the holes performed worse than V-3Hm-3.3 in terms of both, initial rigidity and maximum proof strength.

Figure 8 shows the load deflection relationship in the horizontal insertion group.

These specimens behaved similarly to the unreinforced specimens.

The superiority of openings and dowels was not clear in these specimens.

3) Fracture behaviour

Figure 9 shows the fracture behaviour of vertical series.

The cross-section of the specimen with the wood cut away is shown.

The beam fractured in bending tension from the centre of the beam.

In V-4Hm-3.3, the facture shape shows that the wood fracture progress roughly along the rupture of the steel sheets.

V-3Dm-4 showed a similar fracture shape.

Figure 10 shows the fracture behaviour of H-N.

Bending and tensile fracture from the centre of the beam.

The steel sheet on the tension side was broken from the band.

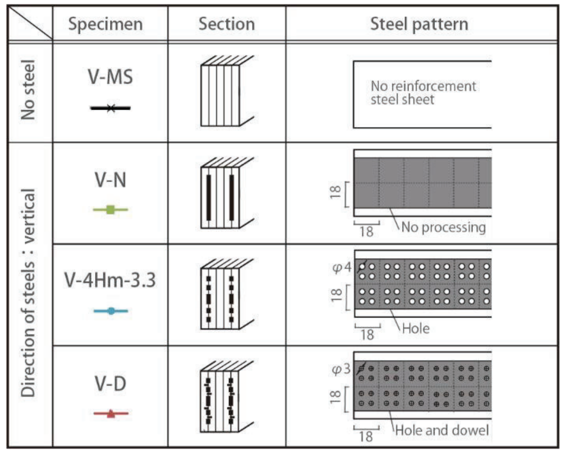

Figure 5: *Specimen parameters of vertical series in phase 1*

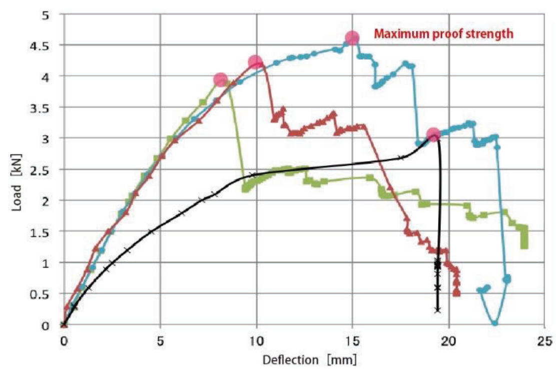

Figure 6: *Load-deflection relationship in vertical series*

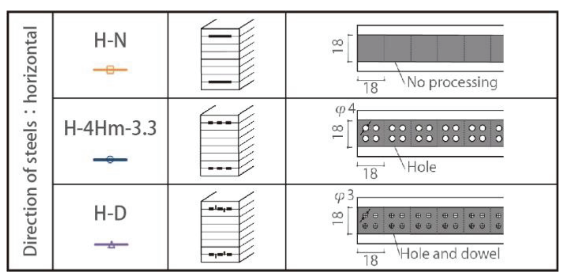

Figure 7: *Specimen parameters of horizontal series in phase 1*

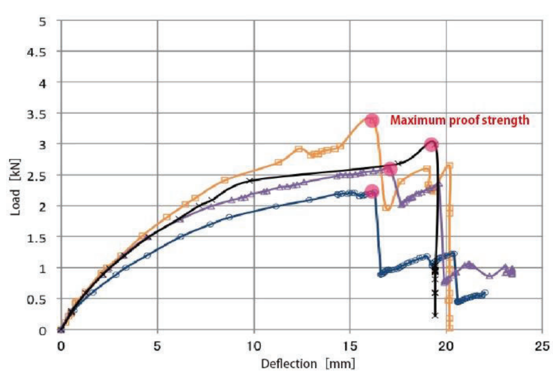

Figure 8: *Load-deflection relationship in horizontal series*

4) Discussion
The specimens with vertically inserted steel sheets had better initial rigidity and maximum proof strength.
Specimens V-4Hm-3.3 and V-3Dm-4, in the load-deflection diagram showed an increase in toughness with repeated load decreases and recovery after the maximum proof strength.
The progression of the fracture from the outermost band to the next band of the steel sheet on the tension side was repeated, and the wood followed the fracture.
The thin steel sheet and its holes resulted in a highly integrated cross-section of wood and steel.
V-3Dm-4 with dowels applied to the holes performed worse than V-3Hm-3.3 in both, initial rigidity and maximum proof strength.
This experiment did not confirm the superiority of dowels.
The reason for this is thought to be a defect in the processing method of the dowel section, inferred from the V-3Dm-4 fracture developed from the v-cut section at the base of the dowels.

4.2 [PHASE 2]: EFFECT OF HOLE PLACEMENT

In this phase, specimens were limited to a group of vertically inserted steel sheets.
The main parameters of phase 2 were the placement and size of holes in the steel sheet to confirm if they affected bending performance.

1) Specimen parameters
Figure 11 shows specimen parameters in Phase2.
Specimens were prepared in 6 types.
Three different hole sizes (5.5 mm, 6.5 mm, and 7.5 mm) were prepared.
One specimen had a grid arrangement of holes in the steel sheet (V-5Hg-6.5) and three had staggered holes.
V-MS and V-N had the same configuration as the specimens in phase 1.

2) Results: Load-deflection relationship
Figure 12 shows the load deflection relationship in phase 2.
Initial rigidity was improved for all specimens over that of simple laminated wood beams.
Almost all the specimens had higher maximum proof strength than simple laminated wood beams. Only V-5Hg-6.5 was inferior.
V-5Hg-6.5 was likely defective because the behaviour of the load-deflection diagram was unstable during the early stages of loading.
V-N had the largest initial rigidity and maximum proof strength, but low toughness.

3) Fracture behaviour
Figure 13 shows the fracture behaviour of V-N.
The specimen fractured in the middle of the beam so that the fibres of the tension side wood were severed.
The steel sheet band lifted approximately 3 mm from the wood.
Figure 14 shows the fracture behaviour of V-5Hg-6.5.
The specimen fractured in bending tension from the centre of the beam.

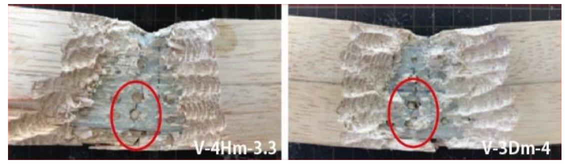

Figure 9: *Fracture behaviour of vertical series*

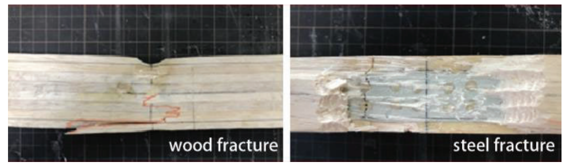

Figure 10: *Fracture behaviour of H-N*

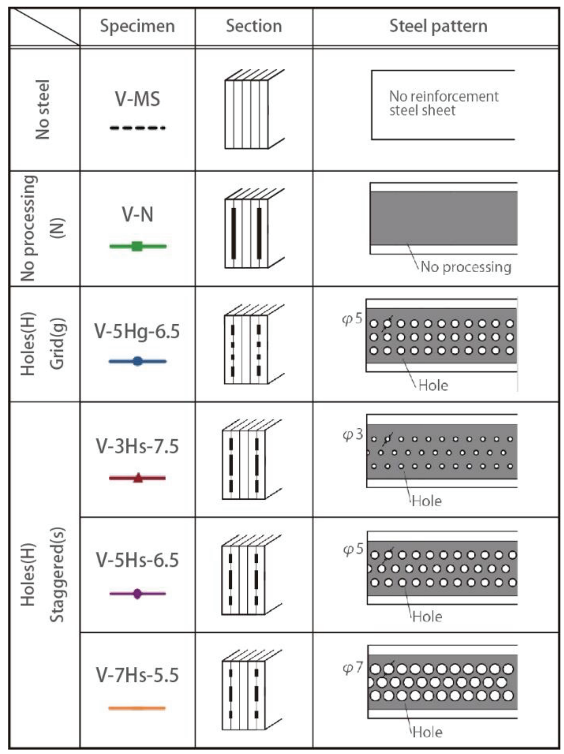

Figure 11: *Specimen parameters in phase 2*

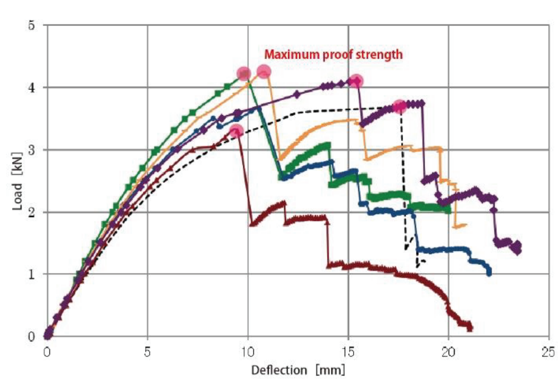

Figure 12: *Load-deflection relationship in phase 2*

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The steel sheet band lifted approximately 0.9 mm from the wood.

4) Discussion
Apart from V-5Hg-6.5, the initial rigidity and maximum proof strength of the specimens were higher than those of simple laminated wood beams.
The insertion of steel sheets improves bending performance.
The specimen reinforced with a steel sheet without holes showed the greatest initial rigidity and maximum proof strength, but the steel was lifted from the wood up to the neutral axis after unloading.
The specimens reinforced with steel sheets with holes showed better toughness.
Hole size showed a trend towards improved performance for larger sizes.

4.3 [PHASE 3]: EFFECT OF BANDWIDTH

Specimens were limited to a group of vertically inserted steel sheets in phase 3.
The main parameter was steel sheet bandwidth, which was tested to see if it affected bending performance.

1) Specimen parameters
Figure 15 shows specimen parameters in phase 3.
Specimens were prepared in 6 types.
Steel sheets were prepared with holes in a staggered arrangement (V-5Hg-6.5, V-5Hs-4, V-5Hs-3, and V-4Hs-3) and modular arrangement.
V-5Hs-6.5 and V-4Hm-3.3 had the same composition as the specimens in phases 1 and 2.

2) Results: Load-deflection relationship
Figure 16 shows the load-deflection relationship in phase 3.
V-5Hs-4 had the greatest initial rigidity.
The specimen with the greatest maximum proof strength and toughness was V-4Hs-3.

3) Fracture behaviour
Figure 17 shows the behaviour of V-4Hs-3.
The tension side of the wood fractured near the loading point.
In the tension side, the band lifted1.2 mm out of plane.
Figure 18 shows the behaviour of V-5Hs-4.
V-5Hs-4 also showed a similar fracture shape to V-4Hs-3.

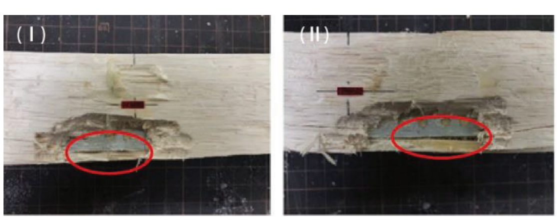

Figure 17: *Fracture behaviour of V-4Hs-3*

Figure 13: *Fracture behavior of V-N*

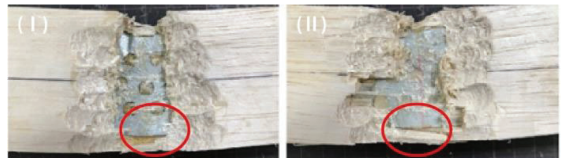

Figure 14: *Fracture behavior of V-5Hg-6.5*

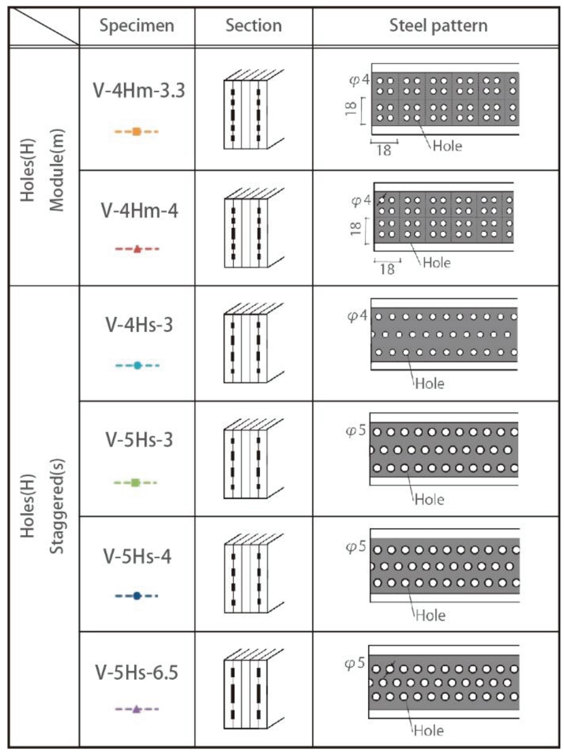

Figure 15: *Specimen parameters in phase 3*

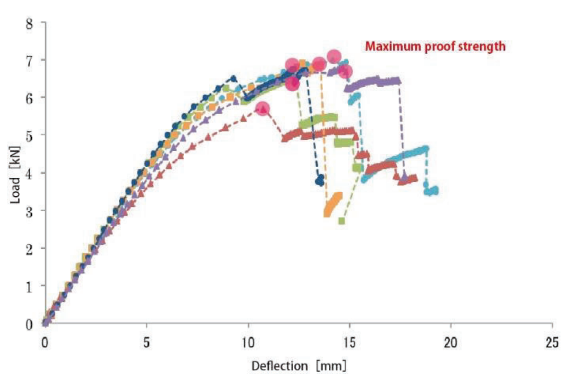

Figure 16: *Load-deflection relationship in phase 3*

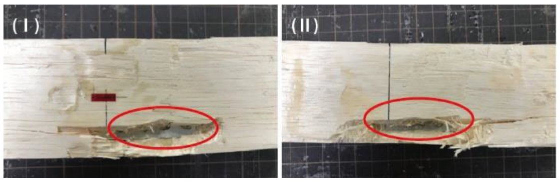

Figure 18: *Fracture behaviour of V-5Hs-4*

4) Discussion
No clear effect of the bandwidth parameter on bending performance could be observed.
Regarding the placement of holes, there was a slight performance improvement trend towards staggered placement.
The staggered arrangement may be due to the homogenisation of stress transmission in the cross-section, as the bands of the steel sheets intersect at an angle.

5 GENERAL OBSERVATION

The insertion of steel sheets was observed to improve bending performance.
Specimens with vertically inserted steel sheets had better initial rigidity and maximum proof strength than those with steel sheets inserted horizontally.
This result suggests that the vertical reinforcement of steel sheets with wood materials is a more effective than the horizontal reinforcement.
The hole size parameter showed a trend towards improved performance for larger sizes.

6 CONCLUSION

The observations from our study can be summarised as follows:
1) Bending performance is improved by inserting steel sheets into the laminated wood.
2) Vertical insertion of the steel sheet is more effective than horizontal insertion.
3) Holes in the steel sheet improve the integrity of the steel and wood sections.

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