PAPER Nr.: 107

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TWENTIETH EUROPEAN ROTORCRAFT FORUM
OCTOBER 4 - 7, 1994 AMSTERDAM

Printed by the Technical Highschool Haarlem

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ABSTRACT

In this study a step by step approach was followed to design a sine-wave spar with the capability to absorb crash energy, to resist shear forces and to show post-crush integrity, with a trigger mechanism that has the potential to sufficiently reduce the peak loads in compression, but without seriously decreasing the shear strength of the spar. This capability was demonstrated on single spars tested in static and dynamic compression, and on a generic subfloor box structure that was tested dynamically. A KRASH analysis of the box overestimated the energy absorption performance that was observed for the box during the drop test, because the dynamic characteristics of the individual components of the box were not available at the time the analysis was carried out, and static characteristics were used instead.

Future developments are described that are directed at establishing the effectiveness of the trigger mechanism of the sine-wave spar when this spar is integrated in a generic subfloor box, loaded by water pressure at the bottom skin as encountered during water impact conditions, for which a novel tensor-skin concept will be employed.

Keywords: Crashworthiness, Sine-wave Spars, Trigger Mechanisms, Water Impact.

1. INTRODUCTION

Future military helicopters will, to a large extent, consist of composite materials to permit lighter structures. Simultaneously, the design of such helicopters will have to satisfy more stringent and still developing crashworthiness specifications. The study presented here is part of a research activity carried out at the National Aerospace Laboratory NLR in the Netherlands, to develop structural concepts for the enhanced energy absorption capability of composite helicopter structures.

Sine-wave spars are being used specifically by the helicopter industry as structural members in subfloor structures because of their superior energy absorption capability compared to other spar geometries. Drawbacks of the sine-wave spar concept, however, are the high production costs, the complicated interfacing (for instance with adjacent fuel tank bladders), and the difficulty to incorporate a suitable trigger mechanism. Trigger mechanisms are needed to reduce the peak load in compression during survivable crash conditions, thereby preventing spinal injuries to the occupants of the helicopter, however, without affecting the shear strength of the spar which is needed during operational loading conditions. The study presented here focuses on the development of a concept for a satisfactory trigger mechanism to be used in composite sine-wave spars.

2. DESIGN

The sine-wave spars used in this study were designed for "generic" loading conditions, i.e., for a shear loading of 220 N/mm, with a wall thickness of approximately 1.2 mm for stability. More attention was paid to the following aspects, which were all addressed in preliminary studies:

- material selection
- fabrication techniques
- laminate composition
- included web angle
- web/flange connection
- trigger configuration

a. material selection

According to many sources in the literature, a combination of carbon fibers and aramid fibers gives optimum crash energy absorbing characteristics: the high strength and stiffness of carbon fibers to absorb energy, and the resilience of aramid fibers to provide post crush integrity and to contain the carbon fibers so they will break in many small fragments. In the study presented here a hybrid carbon-aramid crow foot weave was used to form the outer layers of the laminate used for the web, combined with unidirectional carbon fiber layers to form the core of the laminate, with the fiber direction running parallel to the compressive loading.

b. fabrication techniques

The sine-wave spar is a complicated part to manufacture in one shot. For this reason NLR granted a contract to the Aerospace faculty of Delft University, to evaluate the possibility to manufacture sine-wave spars out of thermoplastic material, using a diaphragm forming process. This option turned out to be uneconomic, hence, epoxy was chosen as the matrix material for further developments. Both the RTM technique and the hand lay-up/autoclave technique were used to develop test articles, but the test programme described here was carried out using specimens made with the latter technique only, (some by Fokker Aircraft B.V.), which was available in an earlier stage of the development. The materials used for the specimens are listed in Table 1.

c. laminate composition

A preliminary study to establish suitable laminate compositions with respect to their energy absorption properties is reported in Ref. 1. In this study, performed with tubular specimens (Fig. 1), two different failure modes were distinguished: a splaying mode and a fragmentation mode, confirming the findings of Hull, Ref. 2. It was also discovered that a trigger mechanism not only governs the peak force during the initial stage of crushing, but that it may also govern the amount of energy absorption during the subsequent stages, by initiating a favorable or unfavorable crushing mode. A laminate comprising of fabric oriented at 45° and unidirectional plies at 0° with the compression direction turned out to be a good compromise for energy absorption and shear performance.

d. included web angle

The influence of web-geometry, i.e., the included angle of the sine-wave pattern (Fig. 2), on the energy absorption capability of the spar was determined using single web specimens (Fig. 3) as well as complete spars with flanges (Fig. 4). Also, the smallest acceptable angle was sought to facilitate the manufacturing process. A computer code developed at Delft University (DRAPE, Ref. 3) indicated problems with the drapability of the material at large included angles, especially when using a thermoplastic material (Fig. 5). This study is reported in Ref. 4, and an included angle of 100° was found to be optimal for energy absorption per unit mass. However, as thermoset material was to be used, for which the drapability problem is less severe, sine-wave spars with an included angle of 120 were used in this programme, as tooling for this configuration was already available.

e. web/flange connection

Two different spar design concepts were evaluated: single flanged "C"-spars and double flanged "I"-spars, as shown in figure 6. C-spars (Fig. 4) with different included angles and different trigger mechanisms were evaluated first, because they are easier to manufacture. As the post-crush integrity of the C-spar design turned out to be minimal (Ref. 5), the I-spar design (Fig. 7) was evaluated subsequently, and was used for the remaining part of the project.

f. trigger configuration

Several trigger mechanisms (Fig. 8) were incorporated, both in C-spars and in I-spars, of which the results are presented in Ref. 5. Trigger mechanisms were formed by interrupting or dropping off one or more of the unidirectional plies that form the core of the laminate, or by creating eccentricities. The trigger mechanisms were continuous along the full length of the spars. For the I-spar design, the "flange-gap" trigger, constructed by combining a ply interruption with an eccentricity induced by a foil inclusion (Configuration 8 in Fig. 8) was most successful, and was used subsequently in the programme.

3. EXPERIMENTS ON SPARS

a. C-spar with radius trigger

The connection between the flange (or cap) and the web of the C-spar concept is formed by a small curved section (Fig. 8, Configurations 1 and 2). This section by itself forms a trigger mechanism due to the load eccentricity it creates, regardless of the trigger mechanisms specifically designed and incorporated in the web of the spar. Fracturing of this web-flange connection, both in compression and in shear tests (Fig. 9), leads to a significant loss of post-crush integrity and shear strength. A detailed study using tube specimens (Ref. 1) indicated that trigger mechanisms not only reduce peak loads, but also initiate the ensuing crushing mode. It was shown with these experiments as well as with the tests on C-spars that the "radius trigger" described here does not produce a favorable crush mode for energy absorption. This investigation is reported in Ref. 5.

b. I-spar with flange-gap trigger

The I-spar design used in this programme is not only more rigid than the C-spar because of its double flanges, it also contains angle reinforcement layers in the flange-web transition area, see figure 10. The trigger mechanism, selected on the basis of the results presented in Ref. 5, consists of a gap in one of the two main load carrying 0 layers, positioned just above the ending of the reinforcement layers. This trigger concept was shown to produce a benign and predictable failure mode, a crushing mechanism with sufficient energy absorption potential, and satisfactory post-crush integrity.

Sine-wave spars made according to this concept were tested in static and dynamic compression. The static tests are reported in Ref. 6. The crushing sequence is shown in Fig. 11 and a representative test curve is shown in Fig. 12. Initial failure takes place due to the trigger mechanism, followed by a stage where the upper part of the web shears at a relatively low load into the lower part of the web with the angle reinforcements, until the web bottoms and picks up load. The shearing mechanism locks the web in place, preventing it from buckling away and escaping further loading. After bottoming the web was shown to resist an average load of 35 kN over a stroking distance of 190 mm.Two dynamic (drop-) tests were performed at DLR in Stuttgart, one on a spar in a horizontal position and one on a spar at an inclined angle (10° out of plane). The failure sequence was identical to that observed in the static tests, but the average loading was 17 kN in the first test, and increased from 10 to 18 kN in the second test, both over a stroking distance of 190 mm. It was concluded that the sine-wave spars in a dynamic test consume approximately 50 % of the energy absorbed in a static test, while the web locking mechanism, which occurs after the trigger fails, provides good post-crush integrity both under static and dynamic loading conditions.

A shear test performed at NLR to determine the influence of the flange-gap trigger mechanism on the shear strength was not yet successful, since buckling of the flat transition zones at the ends of the spar led to premature failure. Through private communiction with Chr. Kindervater of DLR Stuttgart it was learned, however, that on the basis of experiments on similar spars, carried out in the mean time at DLR, the flange-gap trigger mechanism hardly decreases the shear strength of sine-wave spars under static loading.

4. DROP TEST OF A GENERIC SUBFLOOR BOX STRUCTURE

The I-spar concept with flange-gap trigger was subsequently incorporated in a generic subfloor box-structure (Fig. 13). The box consisted of four sine-wave spars as described above, joined with four special cruciform connections developed previously to prevent the occurrence of high peak loads (Ref. 6). An interface between the box and the drop weight was constructed to allow the air to escape from the box at impact, see Fig. 14. This box was also drop-tested at DLR in Stuttgart, and the result is shown in Fig. 15.

The spars were shown to function as expected, according to their behavior when tested statically (as the dynamic tests on the spars had not yet taken place), with failure initiating at the triggers, and the web locking mechanism providing good post-crush integrity. The cruciform joints seem to have disintegrated, however, possibly because of the air locked inside them during the impact.

A KRASH analysis was performed on the box structure, with the model shown in Fig. 16, using the spring stiffnesses, which represent the energy absorption characteristics of the eight components (four spars and four cruciforms) as obtained from the static tests. A comparison of the dynamic test results and the KRASH analysis results is shown in Fig. 17. It was concluded that the box structure absorbed less energy than predicted with the KRASH model. However, with the dynamic test data for the sine-wave spars becoming available, indicating the smaller energy absorption capability of the spars when loaded dynamically, this difference can now be explained. A new KRASH analysis with improved spring stiffnesses has not yet been performed, as dynamic data for the cruciforms are lacking so far.

5. FUTURE DEVELOPMENTS

The issue of crashworthiness of composite helicopter structures with respect to water impact accidents has become of significant importance. At NLR, the "tensor-skin" concept was developed to sustain water pressure loads on the bottom skin of a helicopter, and to transfer these loads to the spars (Ref. 7), preventing the premature failure modes which are common for the traditional brittle composites. A demonstration of this concept is shown in Fig. 18, where a sandwich panel, consisting of "regular" laminated faces, is provided with a corrugated core made of polyethylene fiber/epoxy layers. This core with its strong tensile strength provides the skin with the capability to unfold and deflect by forming plastic hinges, before it stretches and eventually fails in tension. The sandwich panel will be incorporated in a future development of a generic subfloor box structure, containing the sine-wave spars as described in this paper, similar to the demonstrator shown in Fig. 19. Before this experiment takes place, however, several small "proof of concept" tests will be performed to see whether a pressure loaded tensor-skin panel is able to compress a sine-wave spar and initiate the trigger mechanism of the spar.

6. CONCLUSIONS

The requirement for crashworthiness of helicopters must be met with innovative structural designs. One example of such a design is the sine-wave spar concept which may be used in the subfloor structure of a helicopter. This concept is well known for its energy absorption capabilities, but it has also certain drawbacks. One of the difficulties that must be overcome before this concept can be successfully employed, is to develop a trigger mechanism to reduce the peak forces in a crash, without seriously decreasing the shear strength of the spar.

In this study a step by step approach was followed to design a sine-wave spar with the capability to absorb crash energy, to resist shear forces and to show post-crush integrity, with a trigger mechanism that has the potential to sufficiently reduce the peak loads. This capability was demonstrated on single spars tested in static and dynamic compression, and on a generic subfloor box structure that was tested dynamically. A KRASH analysis of the box overestimated the energy absorption performance that was observed for the test specimen during the drop test, because the (reduced) dynamic characterisits of the individual components of the box were not available at the time the analysis was carried out, and static characteristics were used instead.

Future developments are directed at establishing the effectiveness of the trigger mechanism of the sine-wave spar when this spar is integrated in generic subfloor box, loaded by water pressure at the bottom skin simulating water impact conditions, for which a novel tensor-skin concept will be employed.

7. REFERENCES

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7) H.G.S.J. Thuis and J.F.M. Wiggenraad. A Tensor-Skin Concept for Crashworthiness of Helicopters in Case of Water Impact. Paper presented at the 50th Annual Forum of the American Helicopter Society, Washington D.C., 1994, also NLR TP 94045 L.

Tabel 1 Materials

Code	Type	Material	Ply Thickness (mm)	Specific mass (kg/m3)
TenCate CD-553/8475	unidirectional tape	carbon/epoxy prepreg	0.154	1500
TenCate CV-170-40-8475	crowfoot Weave fabric	(60/40) carbon/aramid	0.20	1430

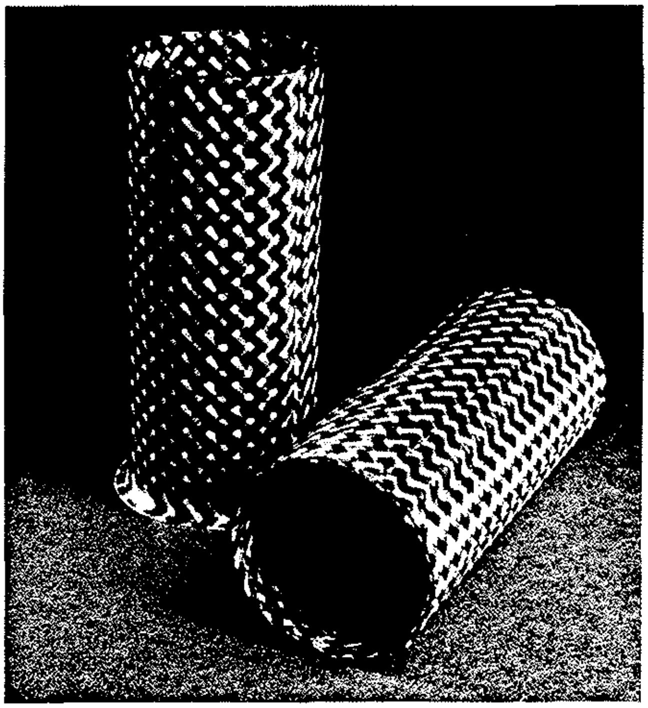


Fig. 1 Tubular specimens with different laminates and trigger mechanisms (Ref. 1)

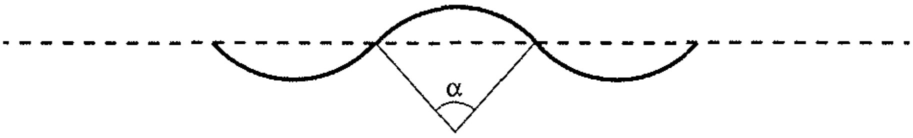


Fig. 2 Included angle of a sine-wave beam web

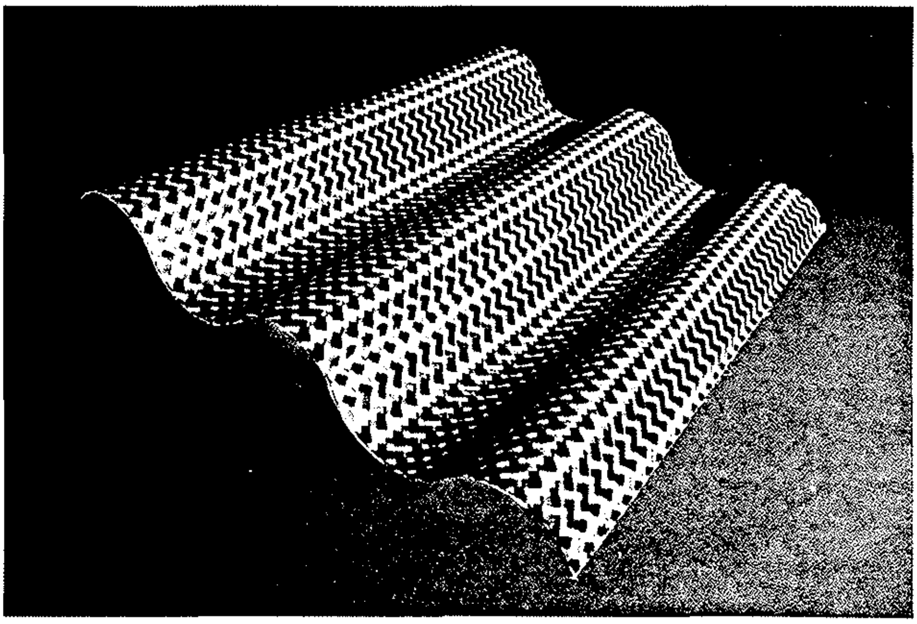


Fig. 3 Single web specimen to evaluate the effect of included angle on energy absorption (Ref. 3)

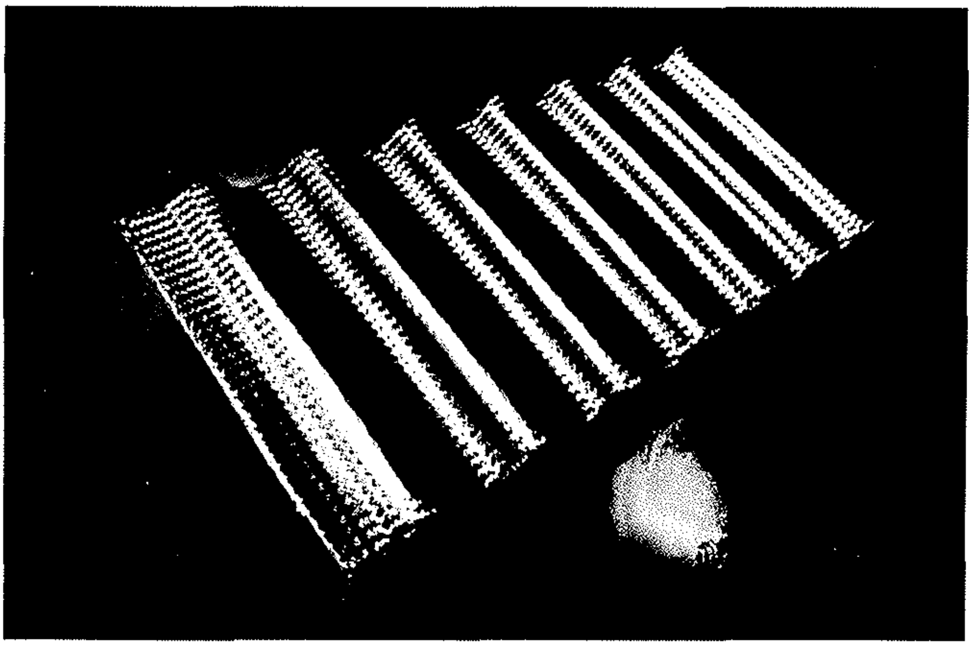


Fig. 4 C-spar

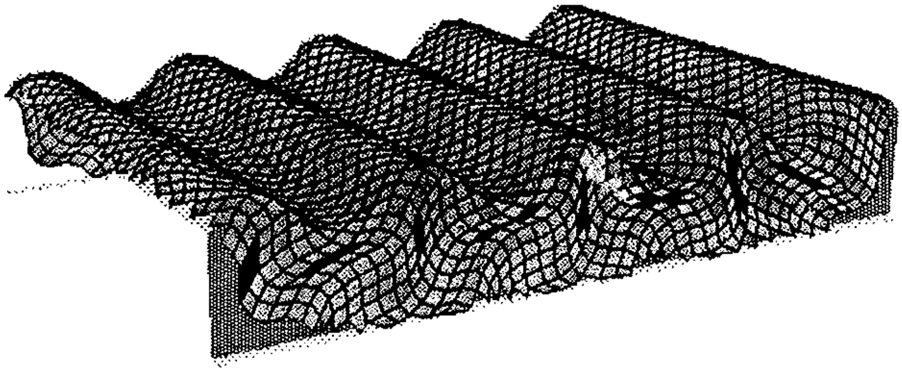
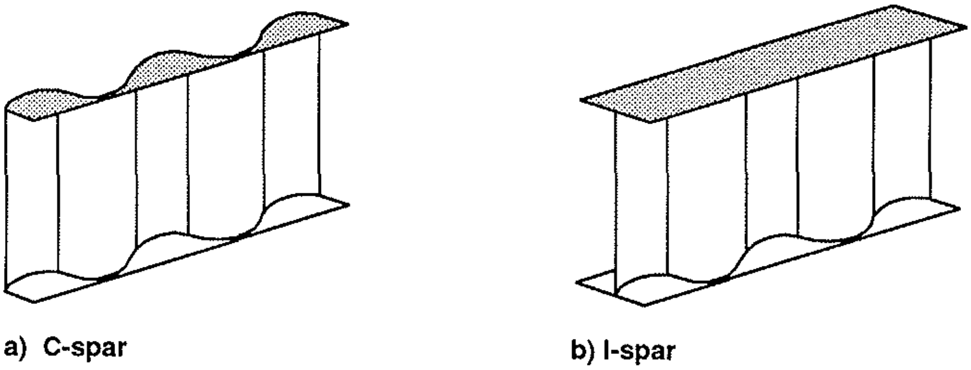


Fig. 5 DRAPE-model of sine-wave (120°) included angle, ∓45° fabric



a) C-spar **b) I-spar**

Fig. 6 Sine-wave spar concepts

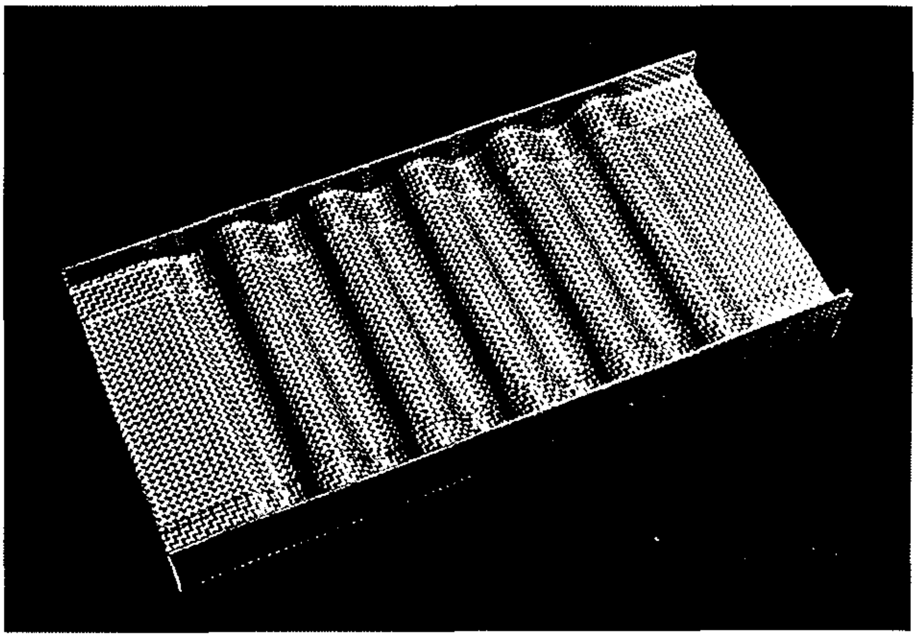
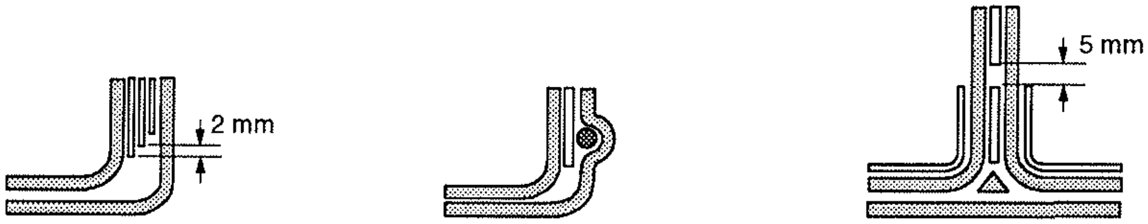
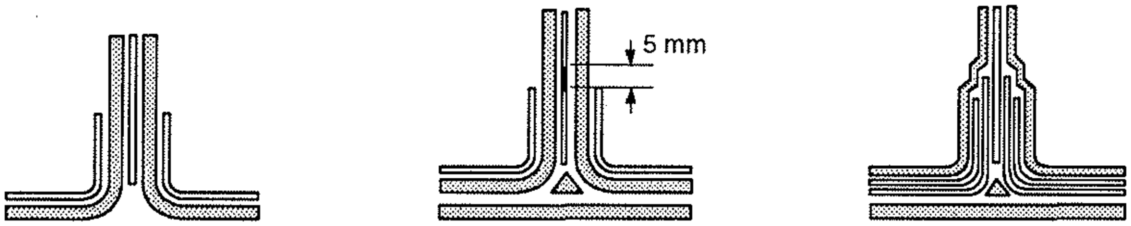


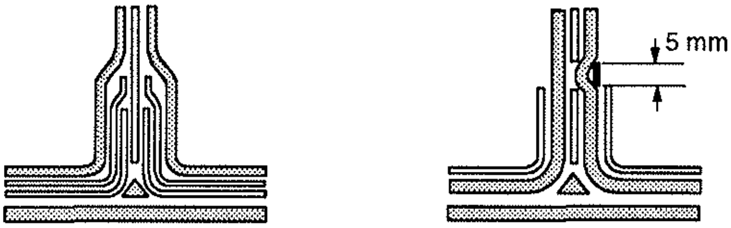
Fig. 7 I-spar



1) 2 mm ply drop-off **2) Eccentric filler** **3) 5 mm gap**



4) Radius **5) Foil inclusion** **6) Reinforcement inside, type a**



7) Reinforcement inside, type b **8) Eccentricity by foil**

Fig. 8 Trigger configurations

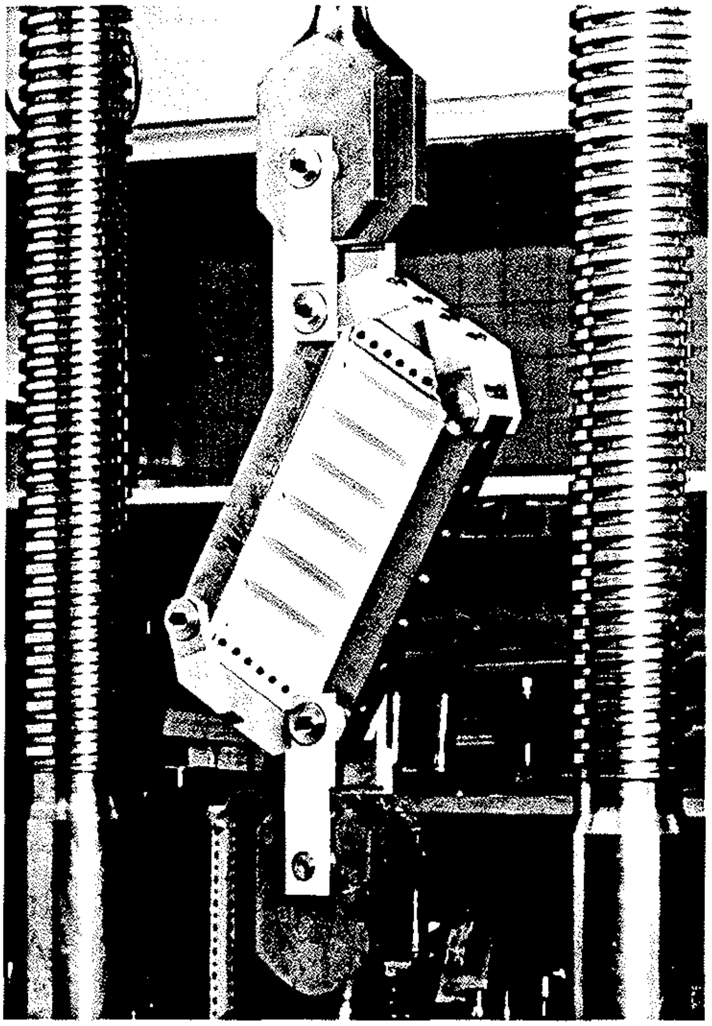


Fig. 9 Shear test setup

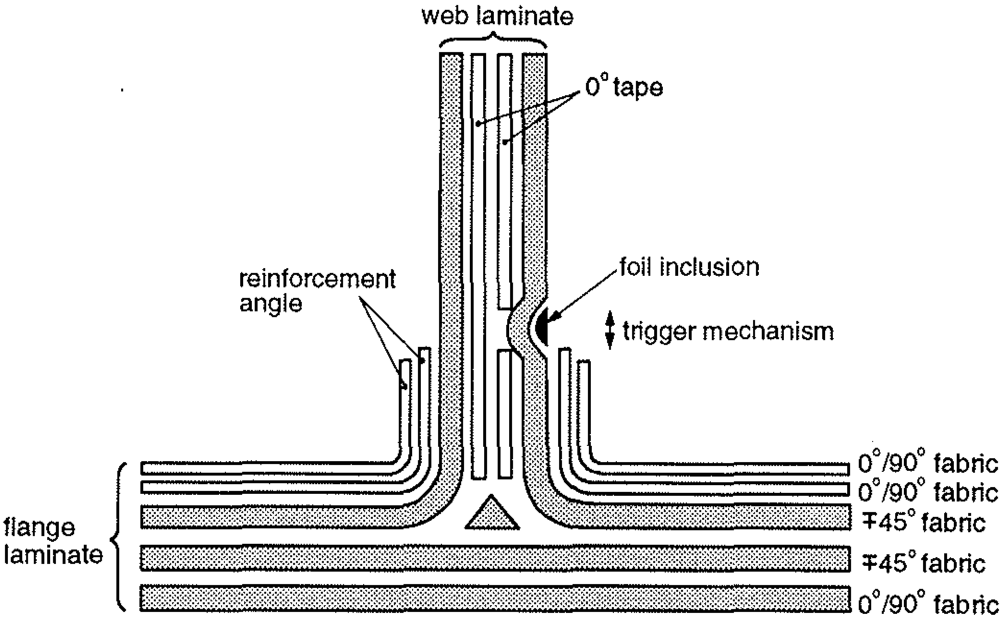


Fig. 10 Flange-gap trigger and detail design of I-spar

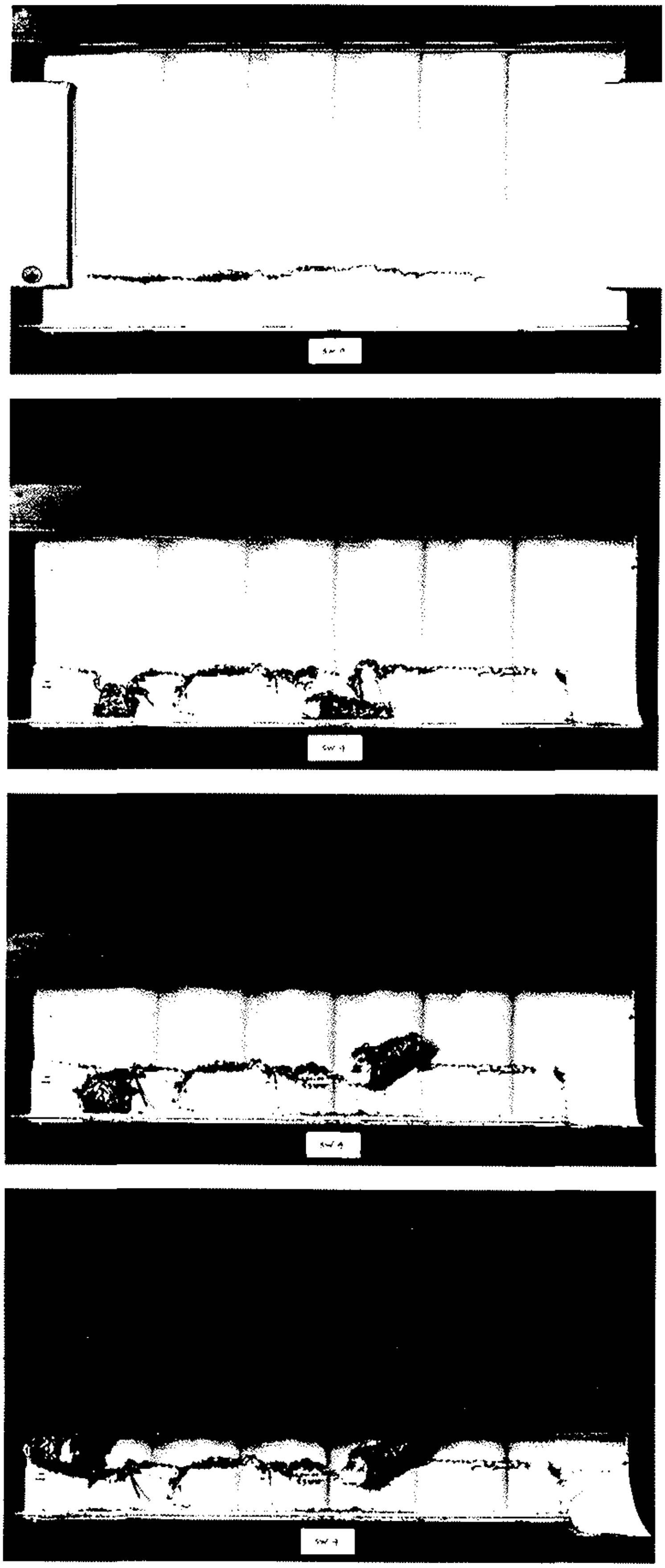


Fig. 11 Crushing sequence of a sine-wave spar loaded in static compression

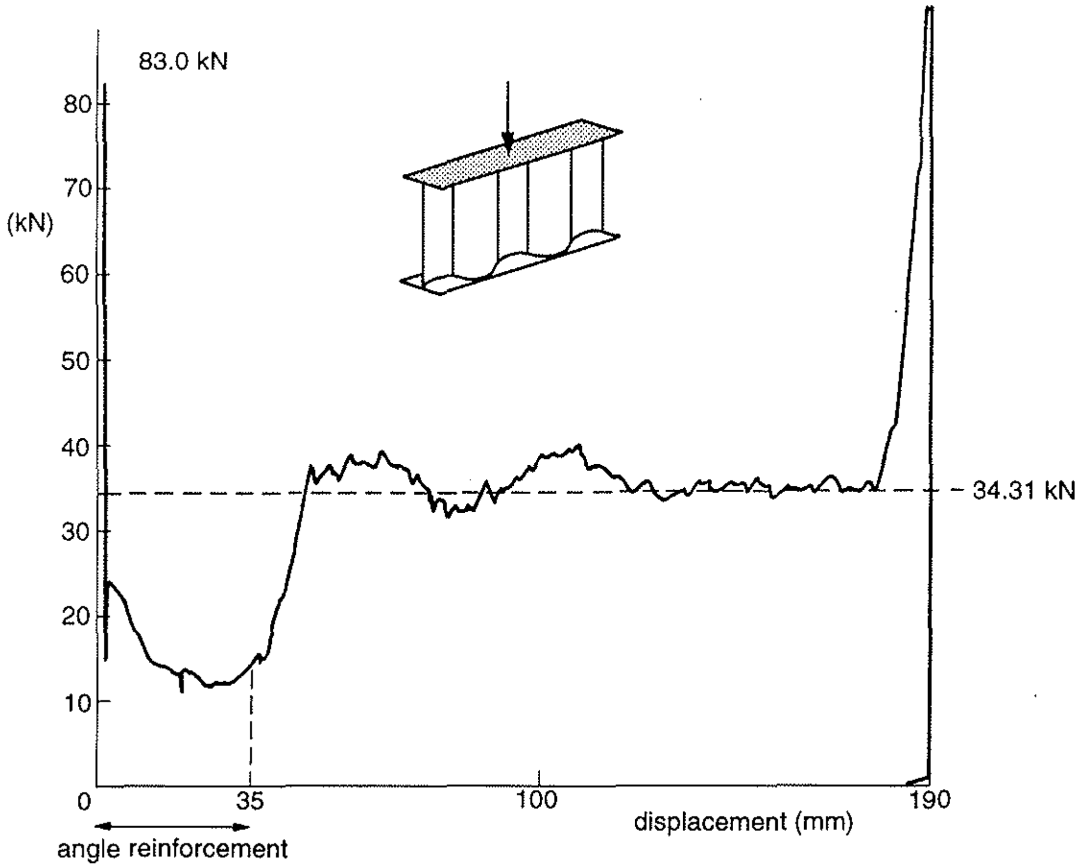


Fig. 12 Load- displacement curve of a sine-wave spar loaded in static compression

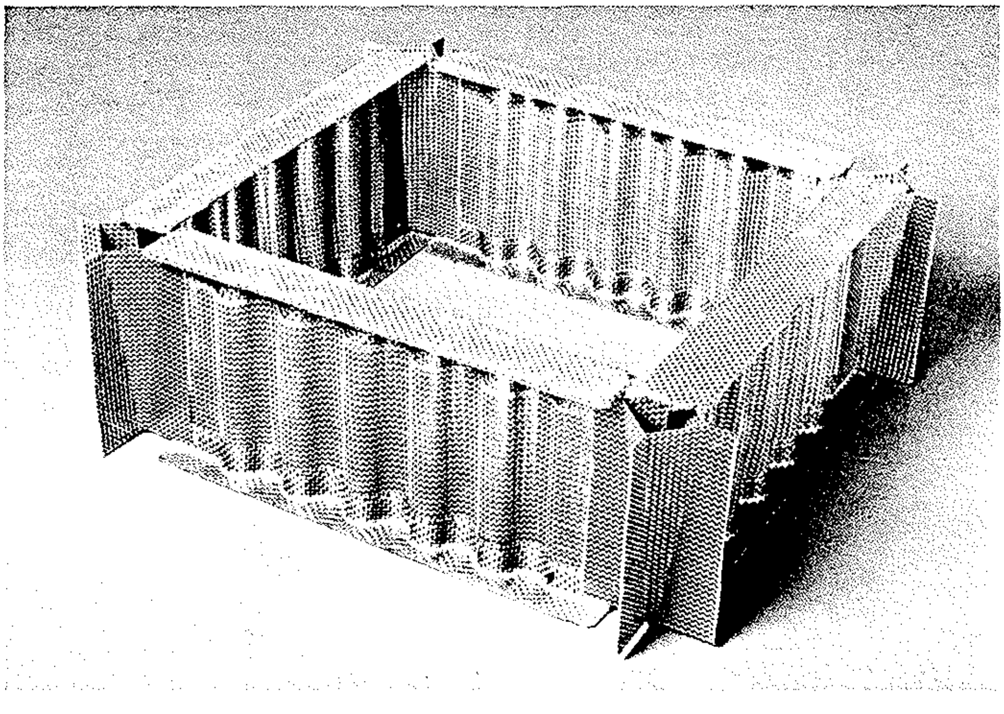


Fig. 13 Generic subfloor box structure

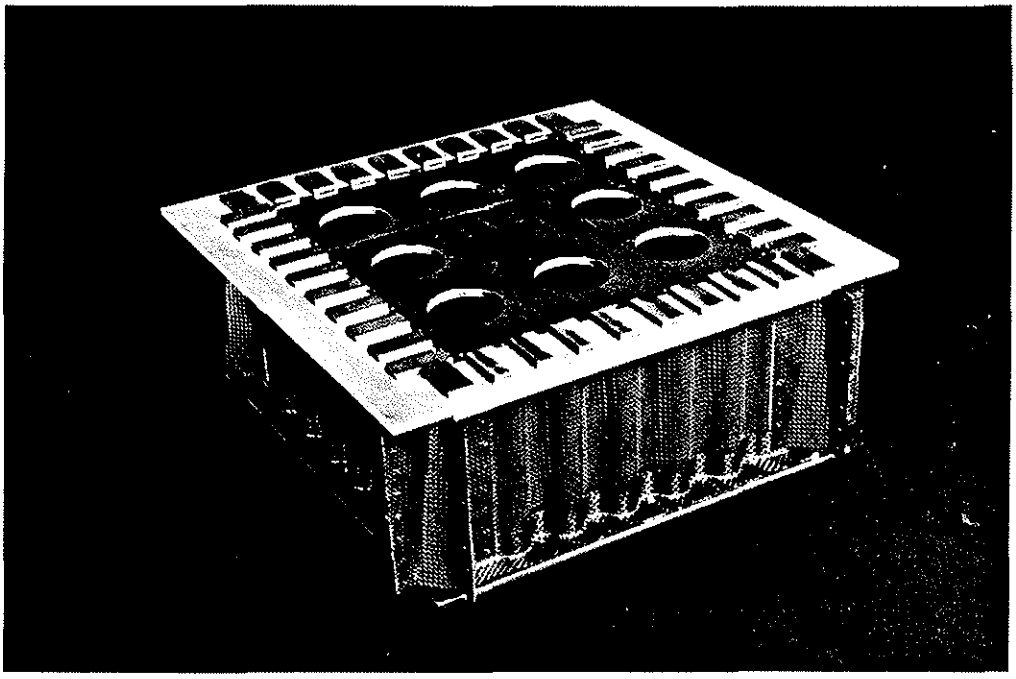


Fig. 14 Box with interface to allow air to escape

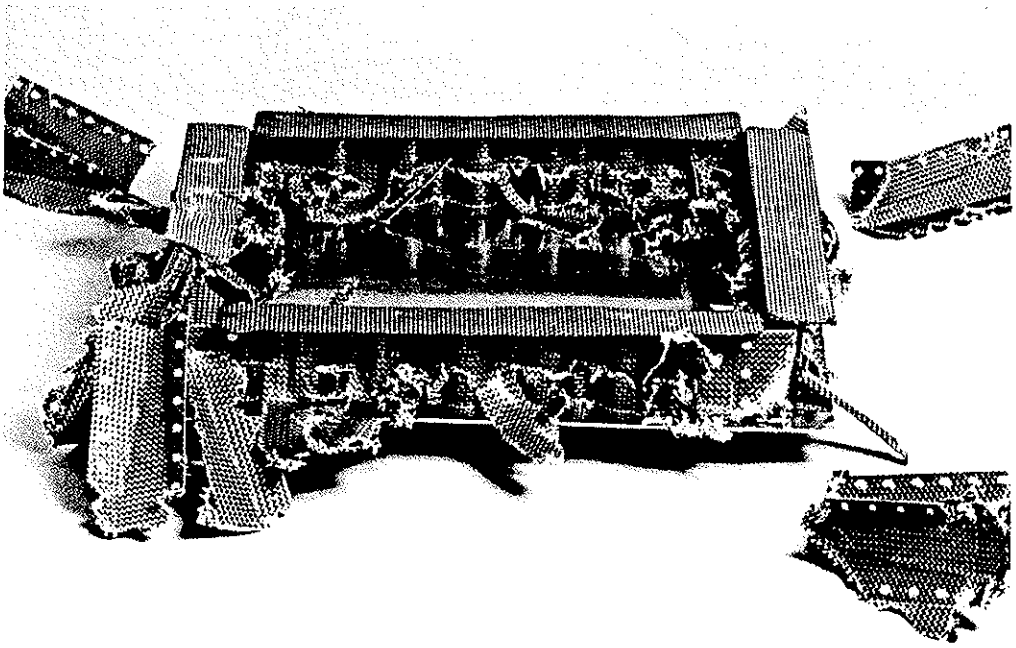


Fig. 15 Box after drop test

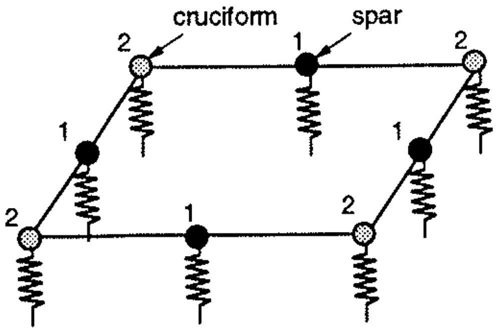
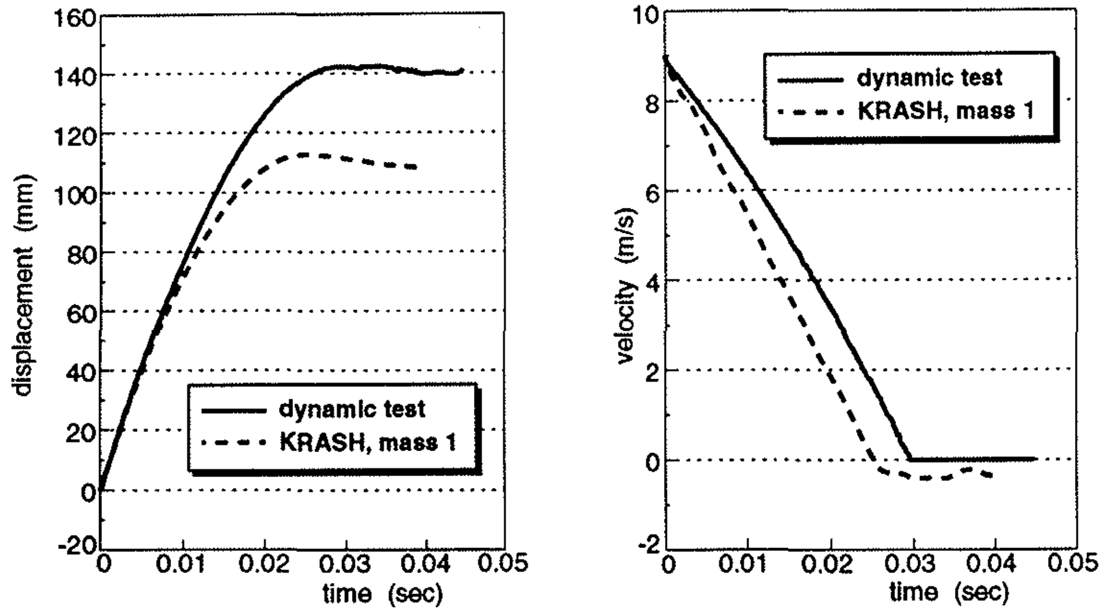
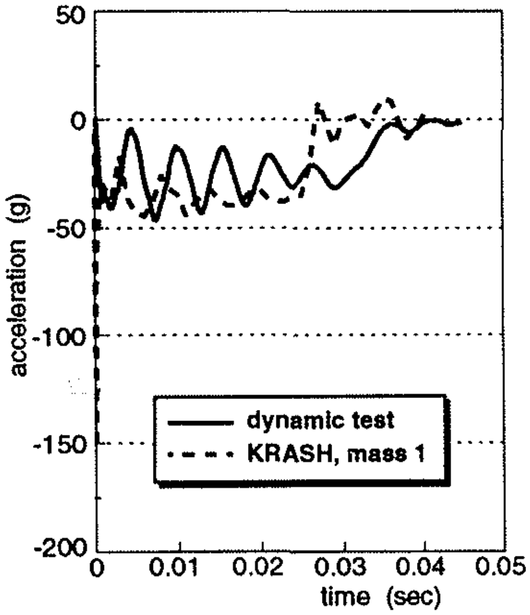


Fig. 16 KRASH model of box structure



a) Displacement history

b) Velocity history



c) Acceleration history

Fig. 17 Comparison of dynamic test results and KRASH analysis

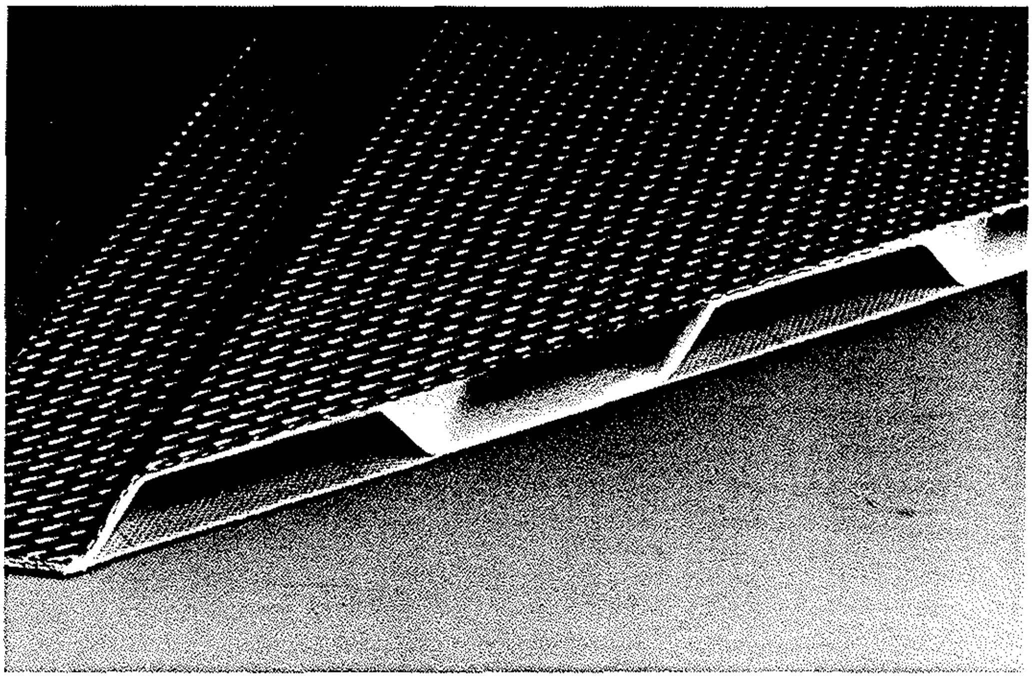


Fig. 18 Sandwich panel with tensor core

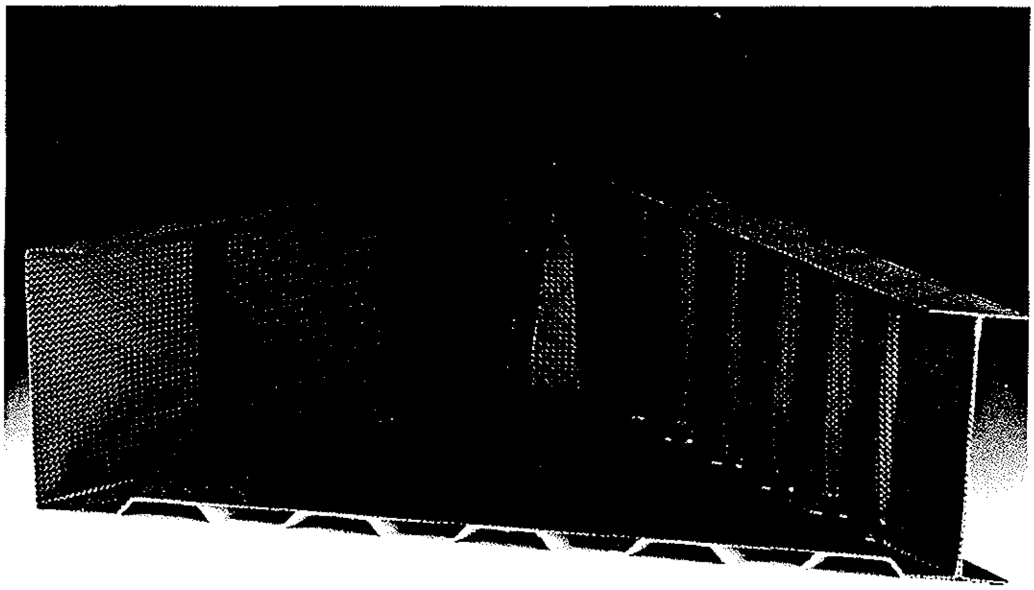


Fig. 19 Generic subfloor box structure with tensor skin panel