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COMPARISON OF THE CRUSHING BEHAVIOUR OF METALLIC SUBFLOOR STRUCTURES

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SUMMARY

Crash loads must be attenuated in the landing gear, the subfloor structure and the seat to values tolerable for the human body. In addition the remaining loads must not jeopardize a living space for the occupants.

A program was undertaken to investigate, both analytically and experimentally, the crushing behaviour of helicopter subfloor structures.

Stiffened panels and honeycomb sandwich panels in metal were considered under quasistatic and dynamic conditions.

The primary intent of the investigations was to design subfloor structures with high efficiency for crash impact and to establish the nonlinear characteristics of subfloor structures as input data for the program KRASH.

This paper describes the behaviour of sandwich panels and compares it with stiffened panels which have been discussed in detail in [5].

1. INTRODUCTION

With the growing importance of crashworthiness not only the loads envelope and system requirements have to be considered in designing the helicopter structure but also crashworthiness requirements according to MIL-STD-1290 (AV). Numerous studies have shown that an improved crashworthiness can create economical benefits although additional costs are generated e.g. [8]. Furthermore an improved crashworthiness is desirable from the humanitarian point of view.

In contrary to flight and landing loads the duties that are created by crashworthiness requirements are partially different or even contradicting. The traditional design principal of lightweight structures - max. strength and stiffness at min. weight - has to be changed as it is necessary to design for controlled failures and stable crushing behaviour. Furthermore the designer has to distinguish between the different areas of the structure. While the underfloor structure as the first impact area has to fulfil primarily energy absorbing duties it is most important to keep the upper structure as a protective shell for the occupants.

As it is highly important to reduce the weight penalty not only a good absolute energy absorption has to be achieved but above all a good specific energy absorption (absorbed energy per mass of absorbing structure). Furthermore it is necessary to obtain a load level as constant as possible over the whole stroke. One reason for this requirement is the necessity that too high load factors have to be avoided and another is again the need to save additional weight.

This paper pesents results from a running development program for an optimized underfloor structure considering the constraints of real size structure as well as from system interfaces.

Due to the development schedule and the more promissing basic behaviour of sheet stringer structure such panels have been tested and optimized earlier and the results have been presented in [5].

Sandwich has been considered to have from its basic behaviour much less energy absorbing potential. Only very few information may be found in the literature about this aspect probably also indicating that there is up to now no application as an optimized energy absorbing structure. But it is a very attractive structure from other points of view. The high specific load carrying capability and the clean surfaces make it advantageous for the designer e.g. for the fuel tank underfloor structure. This was the reason to accept sandwich locally hoping that even sandwich could be improved to a better crushing behaviour. The following report will show how far this was possible.

A comparison of test results and numerical calculations of sandwich specimen under crash loads will be presented too as it was an important topic to investigate the possibility to replace expensive and timeconsuming tests by numerical simulations.

2. GENERAL REMARKS

The investigations summarized in this paper are related to light or medium cargo/utility helicopters in conventional design with fuels tanks in the underfloor structure (Fig. 2-1). The latter creates special constraints to be considered due to structural dimensions and system interfaces.

During the system definition phases it was always tried to avoid sandwich in the underfloor structure due to the basically poor crushing behaviour. In this area mainly build up structure was prefered, which should have more energy absorbing potential.
But sandwich structure is very attractive due to the high specific load carrying capability and the clean surface being an excellent interface to the bladder fuel tanks.

Therefore the program was sequenced in the following steps:

1) To make basic investigations about possibilities to improve the energy absorbing capability.

2) To develope real size crashworthy sandwich structure if sufficient improvements could be reached and the application seems to be the best compromize.

3) To establish input data for the program KRASH.

The basically poor crushing characteristic seems also to be reflected in the small extend of publications dealing with that kind of structure under the aspect of crashworthy design. But from an in house performed research program some very helpful informations could be found (see chapter 3) leading to a more direct approach.

The basic investigations were performed on small samples to study improved trigger and tuning devices. They turned out to have thoroughly suitable means to improve the behaviour. With the understanding of the most promissing features together with the specific requirements of the in the meantime defined areas of sandwich application in the underfloor structure the full size test samples could be defined.

The underfloor structure together with the landing gear are the main energy absorbing systems of a helicopter. The crashworthy seat although very important for the pilot himself takes only a negligible part of the total kinetic energy. Furthermore the structure is of great importance as the energy absorption of the landing gear may be hampered in a crash on muddy soil or in case of a retracted landing gear. In case of a skid type landing gear the structure is of primary importance as the energy absorbing capacity of the landing gear is limited.

For the assessment of structural concepts concerning energy absorption as well as for the optimization process there are a number of criteria on which these concepts should be checked for and compared between each other. The key parameters [4] are shown in figure 2-2. The parameter "load uniformity" has been exchanged from our side by the parameter "efficiency (η)" defined by the reciprocal

$$\eta = \frac{F_{AVG}}{F_{Peak}} \cdot 100\% = \frac{E}{s \cdot F_{Peak}} \cdot 100\% \qquad E = \text{absorbed Energy}$$

In our understanding this definition describes more clearly how far a load deformation characteristic reaches the ideal of a rectangular shape.

Also at MBB system investigations concerning crashworthiness are performed with the program KRASH. As this is a so called hybrid program, contrary to e.g. a nonlinear Finite-Element-program (DYCAST, PAM-CRASH, CRASH-MASS etc.) the linear and nonlinear element behaviour has to be provided as input data.

One way of establishing these data is the component testing another way is to use one of the above mentioned FE-programs as a "preprocessor" for KRASH or to use a combination of both. The latter has been done by MBB in this project in a collaboration with Engineering System International (ESI) using the program PAM-CRASH. The objective was to test the maturity of such a program system for the application of typical aircraft structures with features like rivet connections, thin sheets, sandwich parts etc. instead of automotiv structures for which the quality has already been proved.

As described in [5] and [6] this program proved to be powerful in the application for sheet-stringer structure due to former experience. But this experience was not available on sandwich structure. After some deeper discussions it was decided not to simulate full size panels in the first step but to start with the simulation of the behaviour of small samples parallel to the experimental program of step 1 (see above). A comparison of the results will be given in chapter 5.

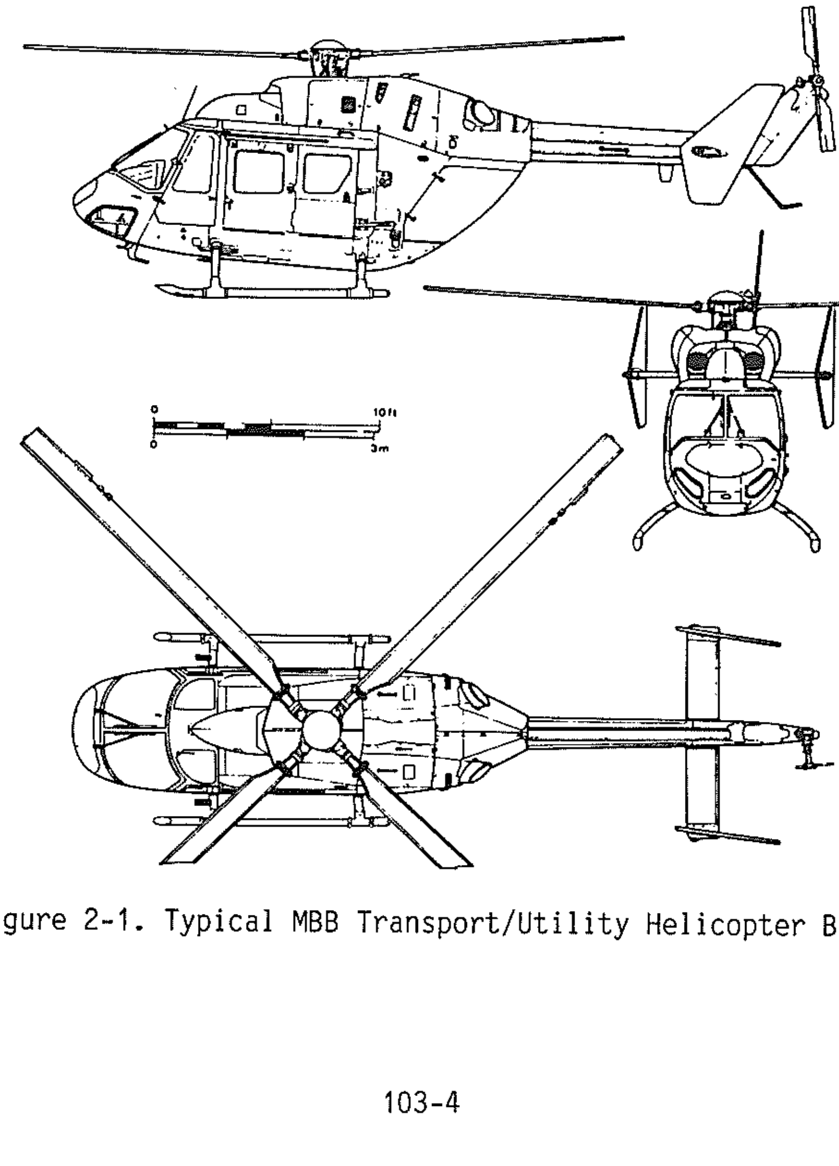

Figure 2-1. Typical MBB Transport/Utility Helicopter BK 117

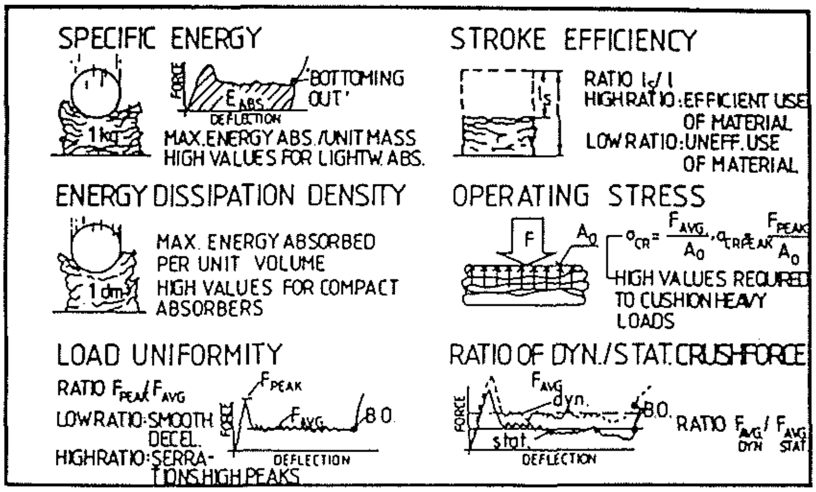

Figure 2-2. Key Parameters of Energy Absorption

3. PREVIOUS WORK AT MBB

As mentioned before there is only very few information in the literature about the crushing behaviour of sandwich structures. Some very useful experience could be collected at the MBB-Bremen plant (former VFW) in a crash research program. This program was sponsored by the German Ministry of Defence in the years 1978 to 1981.

In this program many possible structural concepts have been investigated statically and dynamically.

Among other concepts the following types of sandwich structure have been investigated statically:

1) Foam core with flat cover sheets
2) Foam core with cover sheet having outward beads (see Fig.3-1)
3) Crash core with flat cover sheets
4) Crash core with cover sheets having outward beads
5) Crash core without cover sheets
6) Compound component with crash core and cover sheets with outward beads

The following 4 types of sandwich have been tested dynamically with box type samples (see Fig. 3-2)

1) Foam core with flat cover sheets
2) Foam core with cover sheets having beads
3) Crash core with flat cover sheets
4) Crash core with cover sheets having beads

As a summary the following results could be extracted leading to our approach which is described in the following chapters.

1) The basic sandwich behaviour is quite poor, characterised by a very high load peak and a unstable, uncontrolled behaviour after the first failure (Fig. 3-3).

2) Crash core may improve the characteristic but the behaviour is still quite unstable and the crash-core gives a considerable weight penalty.

3) The beads are a suitable mean to control the failure load but the further crushing behaviour is negatively affected by face seperation.

4) Pure crash core is not able to be a load carrying part in the structural concept of the normal service loads. This is according to our philosophy no suitable approach to reach a weight effective crash structure (see also [5]).

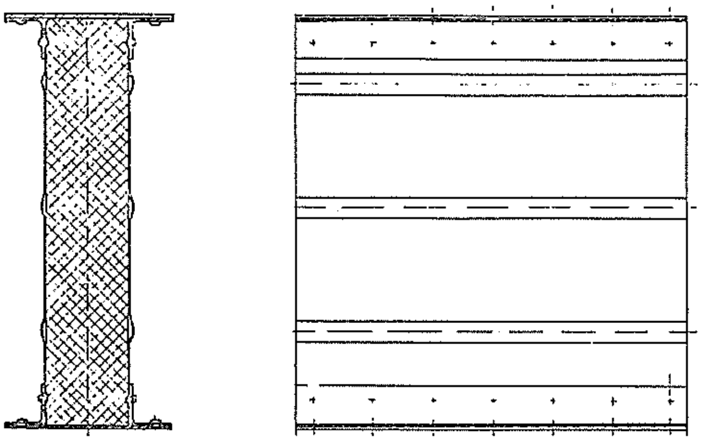

Figure 3-1. Sandwich Specimen with Foam Core and Outward Beads

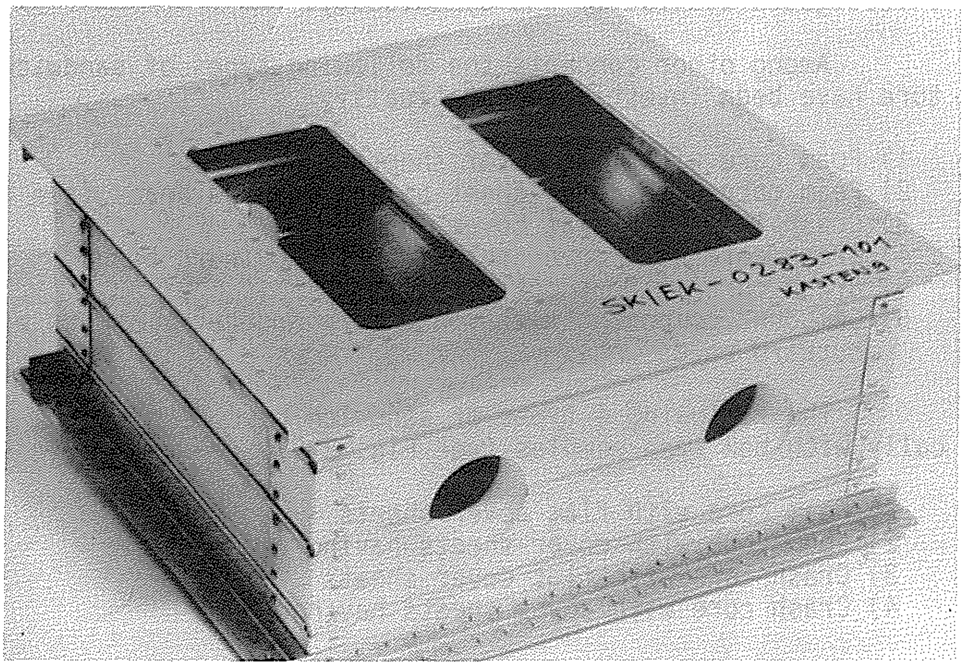

Figure 3-2. Box Type Sandwich Specimen

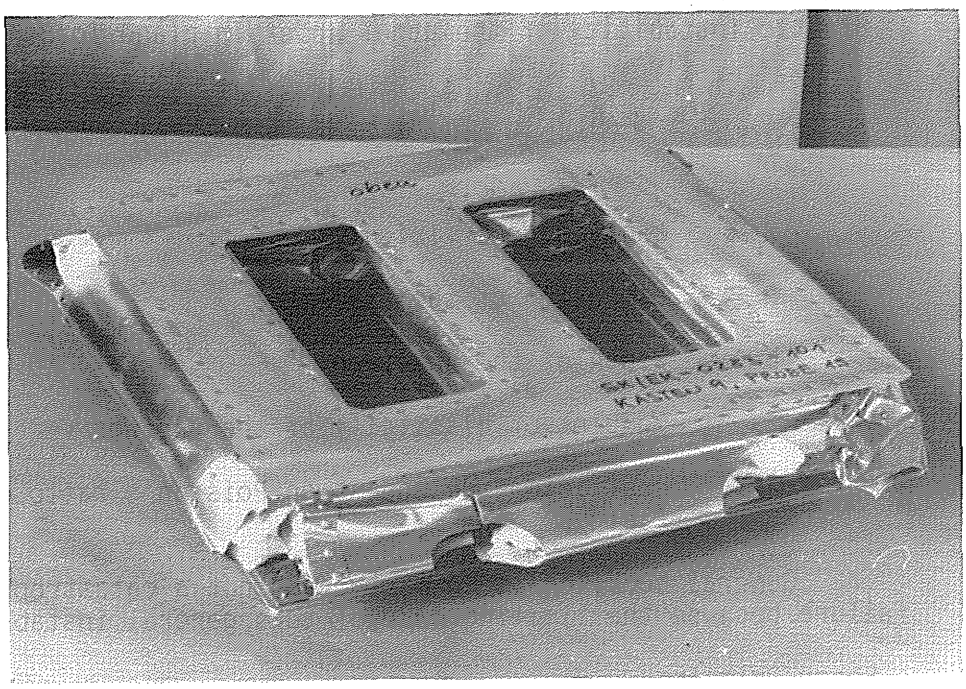

Figure 3-3. Box Type Sandwich Specimen after Dynamic Test

4. DEVELOPMENT AND TESTING OF SANDWICH SPECIMEN

4.1 Theoretical Considerations

According to our philosophy a weight-efficient crash structure may only be built if the design is able to fulfil all the traditional requirements of an airframe and that has in addition enough energy absorbing capability to fulfil certain crash requirements. This led to a sandwich design with face sheets made of aluminium due to the conventional design in that area to reduce risk. The core should be honeycomb due to the much better specific strength and stiffness properties. Both Nomex and Al-honeycomb will be investigated and apart from the crushing behaviour also the corrosion resistance will be a factor for the final selection. The static strength characteristics were determined according to [3]. Unlike to sheet-stringer-structures for sandwich structures several instability or failure modes have to be considered (Fig. 4-1).

Although the failure modes as shwon on Fig. 4-1 are self-explanatory a short discussion using the formulae to determine the respective failure stress shall be given.

For dimensions of the sandwich see Fig. 4-2.

- General Buckling
  Elastic instability of the panel under in-plane loads

$$\sigma_b = \frac{\pi^2 K}{4} \cdot \left(\frac{h}{b}\right)^2 \frac{E_f}{\lambda}$$

K	buckling coefficient
h	dimension of the specimen
b	width of the specimen
E_f	modules of elasticity of the facings
λ	coefficient dependent on Poisson's ratio of the facings

General buckling is in most cases not a catastrophic failure because the limiting case of this general instability is:

- Shear Crimping
  As shear crimping occurs due to shear weakness of the core the formula to determine the failure stress depends mostly on core properties.

$$\sigma_{cr} = \frac{h^2}{(t_1 + t_2)t_c} \cdot G$$

h, t_1, t_2, t_c	dimensions of the specimen
G	shear modulus of the core

- Dimpling of Facings
  Plate-like buckling of the facings with the cell walls acting as edge support

$$\sigma_d = 2.0 \cdot \frac{E_f}{(1 - \nu_e^2)} \cdot \left(\frac{t_f}{s}\right)^2$$

E_f	modulus of elasticity of the facings
ν_e	Poisson's ratio of the facings
t_f	thickness of the facing
s	cell diameter

Although dimpling of facings is tolerable as long as the dimpled region is limited this failure mode can precipitate:

- Wrinkling of Facings
  Final failure from wrinkling usually results either from core crushing, tensile rupture of the core, or tensile rupture of the core-to-facing bond (very improbable with carefully selected adhesive system).

$$\sigma_{wr} = 0.33 \cdot \left(\frac{E_c \cdot t_f}{E_f \cdot t_c}\right)^{1/2} \cdot E_f$$

E_c modulus of elasticity of the core

t_f thickness of facing

E_f modulus of elasticity of facing

t_c thickness of core

Already without any experience from tests it is possible to predict some characteristics in respect of energy absorption related to theses failure modes:

- Shear Crimping is disadvantageous too because the core fails without great in-plane deformation (nearly no plastic deformation). After loss of the core support also the facings don't have, a great energy absorption capability. The failure stress is nearly proportional to h.

- Face Wrinkling is desirable to initiate the necessary deformation provided it is possible to avoid face seperation from the core (see also chapter 3). The failure stress is proportional to the square root of the facing thickness and inversely proportional to the square root of the core thickness. The wrinkling stress has to be reduced as the further crushing stress may not be stabilized on that high level. Possible trigger and tuning devices have to be designed accordingly.

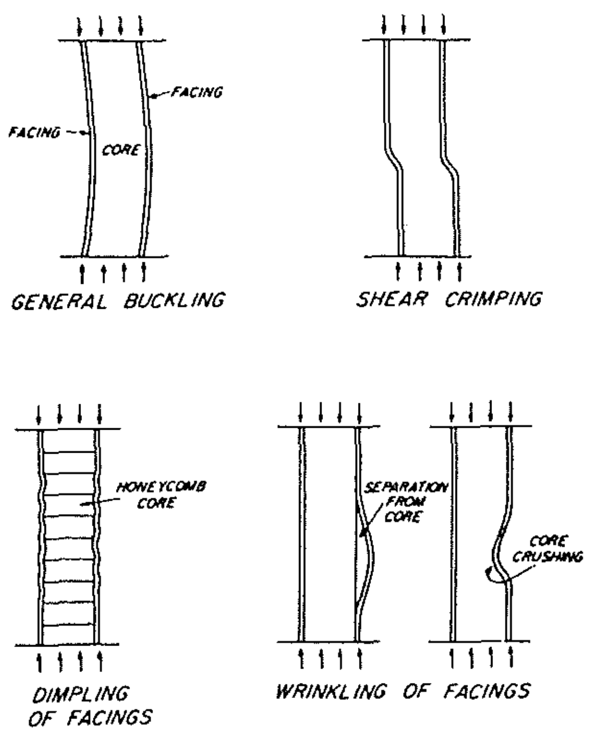

Figure 4-1.

Failure Modes of Sandwich Structures

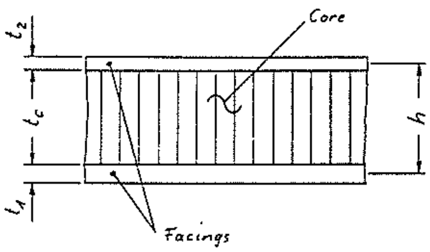

Figure 4-2. Dimensions of Sandwich

4.2 Small Specimen

To get a feeling for the validity of the failure stresses according to [3] and to get a base line in respect of energy absorption quasistatic compression tests of small (150 x 50 mm) specimen with plane facings (and different thicknesses) and two kinds of core (Al- and Nomex honeycomb) have been performed at the beginning.

From Fig. 4-3 it can be seen that it was possible to generate the two limiting failure modes - shear crimping for thicker facings and face wrinkling for thinner facings. During further tests it turned out that [3] predicts conservative wrinkling stresses with increasing accuracy with increasing face thickness. Furthermore it turned out that [3] predicts optimistic crimping stresses with the accuracy having the same trend as for the wrinkling stresses.

During these first tests the typical load-stroke curves as expected were found for unimproved sandwich specimen (Fig. 4-4). Accordingly the energy absorption capability is very poor. The reason is clear: the core does not provide any compressive in-plane stiffness and the compressive in-plane stiffness of the facings is too small to take further load when the support of the core is lost. The poor crash behaviour is deteriorated further when the failure mode is shear crimping. Therefore it was tried to induce face wrinkling by introducing beads in the facings cross to the load direction. From previous tests at MBB (see chapter 3) we knew already that outward beads are disadvantageous because they result in seperation of the facings from the core. Consequently inward dimples were investigated to induce face wrinkling (see Fig. 4-5).

As another reason for these beads was to avoid a very high load peak at the beginning of the load-stroke curve this modification proved to be quite successful. The dimples initiate "further" wrinkling of the facings and crushing of the core under in-plane compressive loading. After contact of the facings the core above and/or below the beads will fail by tensile rupture and the in-plane stiffness of the specimens is reduced further. As an immediate counter-measure the specimens were clamped by screws above and below the dimple. Further specimen were partly filled with foam to avoid core rupture (see Fig. 4-6).

These specimen showed already an improved energy absorption capability but the modifications were not feasible for a production structure. The screws disturbed the plane surface of the specimen and the foam was too heavy. To avoid these disadvantages channel sections were introduced above and below the beads to support the core and the facings (Fig. 4-7).

Although the results were not perfect (also because of the impossibility to clamp the specimen into the test rig) this combination of modifications proved to be a good basis to develope greater specimens.

To verify the quasistatic test results the small specimens were tested dynamically too.

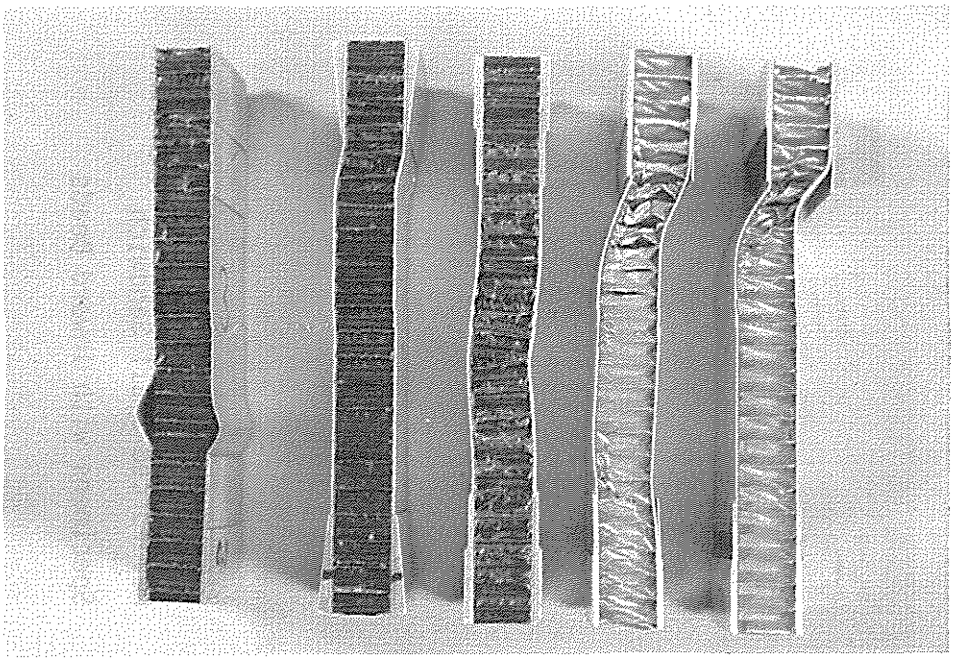

Figure 4-3. Small Sandwich Specimens

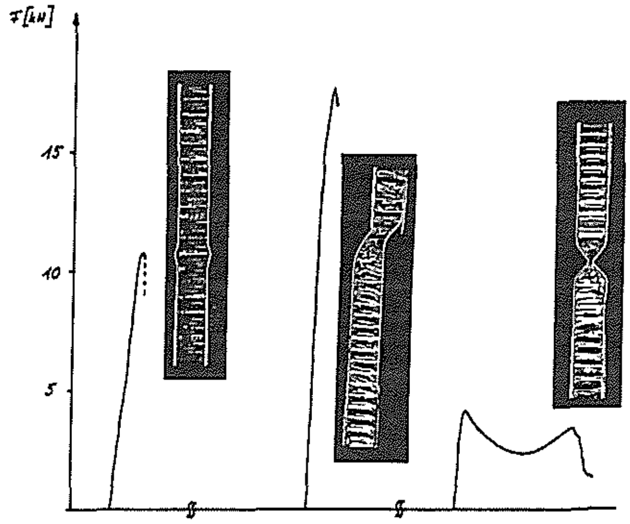

Figure 4-4.

Load-Stroke Curves of

Small Sandwich Specimens

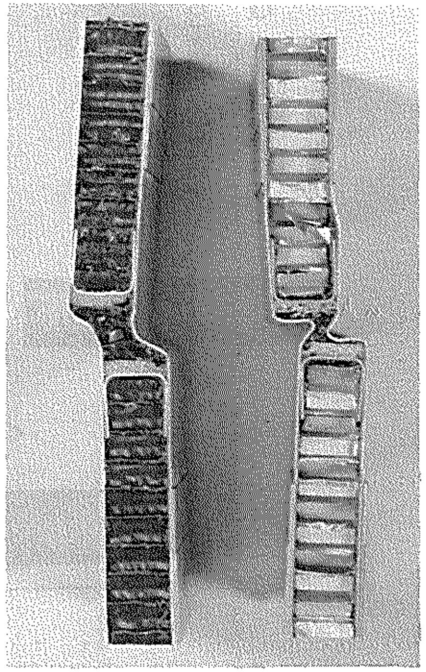

Figure 4-7.

Final Reinforced Small Sandwich Specimens

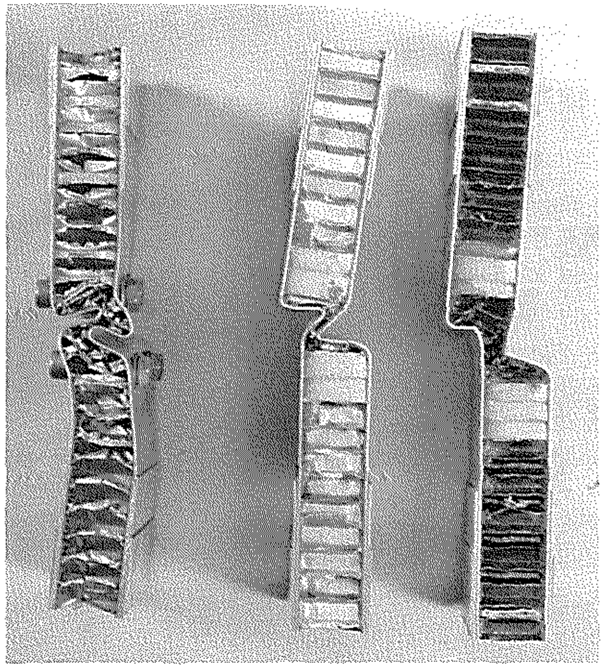

Figure 4-6.

Reinforced Small Sandwich Specimens with Inward Beads

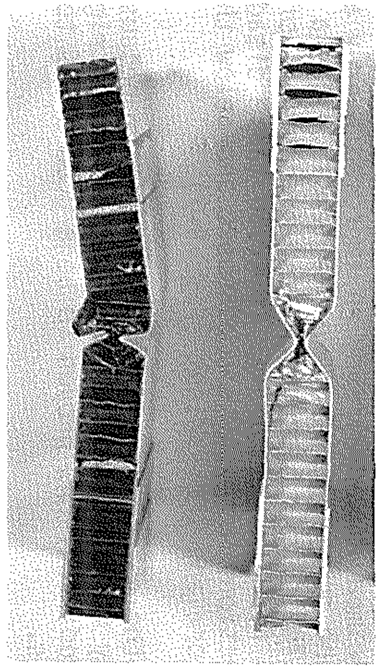

Figure 4-5.

Small Sandwich Specimens with Inward Beads

4.3 Hybrid Specimen

As it is intended for the ALH subfloor structur to build a combination of sandwich and sheet-stringer parts we wanted to investigate the static behaviour of these hybrid specimen at first. The idea was that the sheet-stringer structure which has proved to have a very stable crushing behaviour could reduce the instability tendency of the sandwich structure. The dimensions of the specimen were selected under two principal aspects. The static requirements have to be fulfilled and the overall dimensions have to be comparable with the real subfloor structure. In the sheet-stringer-section and in the sandwich section as well as in the connection of both we introduced the most proven triggers and modifications that were available at that time as there are holes in the stringers, beads and channel sections in the sandwich and notches in the connection angle. The latter had proven very important in tests with sheet-stringer specimen [5] to reduce the undesirable and even dangerous stiffness of crosspoints. In addition the behaviour of symmetrical and asymmetrical beads (see Fig. 4-8) was investigated but in the test results no significant difference could be found.

During these quasistatic tests further modifications were investigated to improve the load introduction into the sandwich section and to improve the behaviour of the connection angle. Although we obtained already quite a good energy absorption it was not possible to seperate the contributions of the different sections. The test results were even a little bit surprising because the visible behaviour of the sandwich section seemed to be not that good. It showed a buckling tendency and seperated from the sheet-stringer part which was induced by beads located in the mid of the plate.

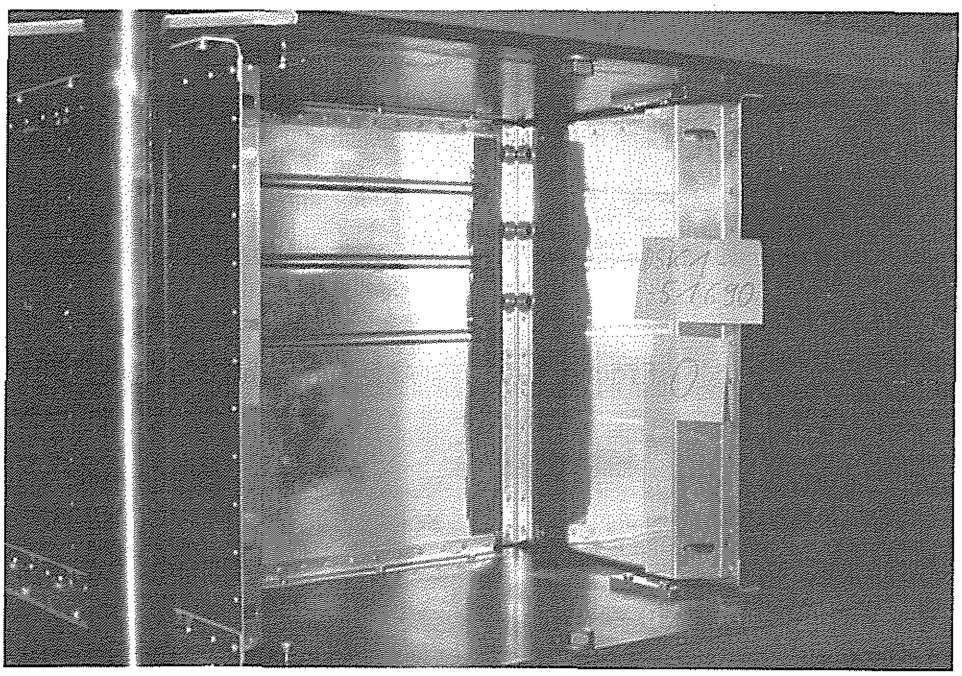

Figure 4-8. Hybrid Specimen with Symmetrical Beads

4.4 All-Sandwich Specimen for Drop Tests

Of course all the know-how that was gathered at that time was employed again. Therefore symmetrical dimples with channel sections were used and special attention was paid to the load introduction and connection angles. In addition the beads were located closer to the load introduction ends to reduce the tendency to general buckling (see Fig. 4-9).

The dynamic tests revealed a reliable trigger functioning (Fig. 4-10) and moreover an unexpected stable crushing behaviour (Fig. 4-11). The load peaks after the first failure remain on a high level and decrease only slightly with the further stroke (Fig. 4-12). But the sandwich shows a strong tendency to structural desintegration after the intended stroke.

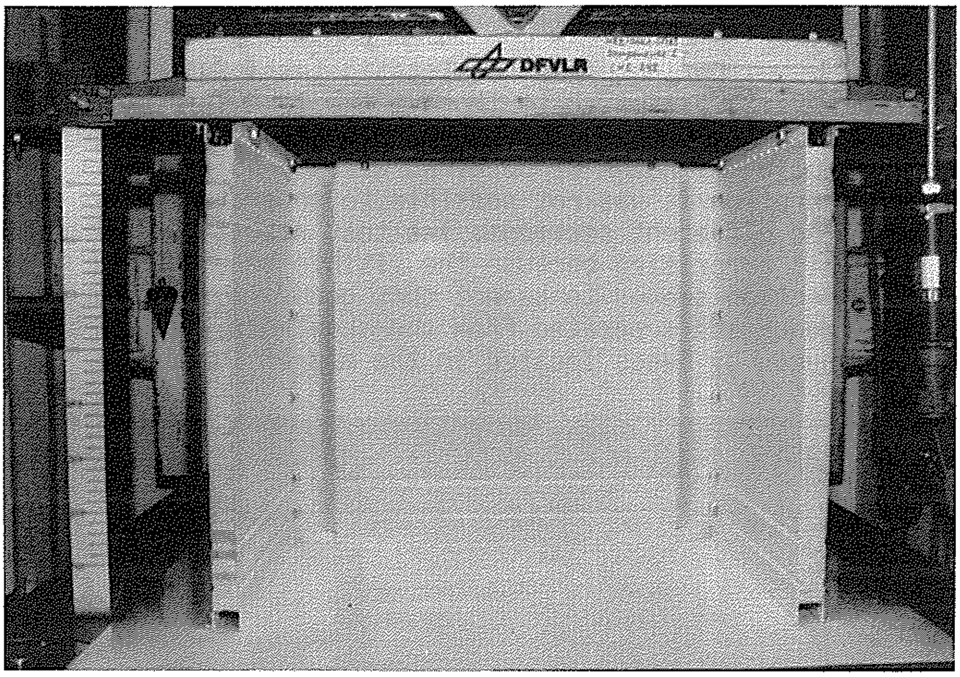

Figure 4-9. All-Sandwich Specimen

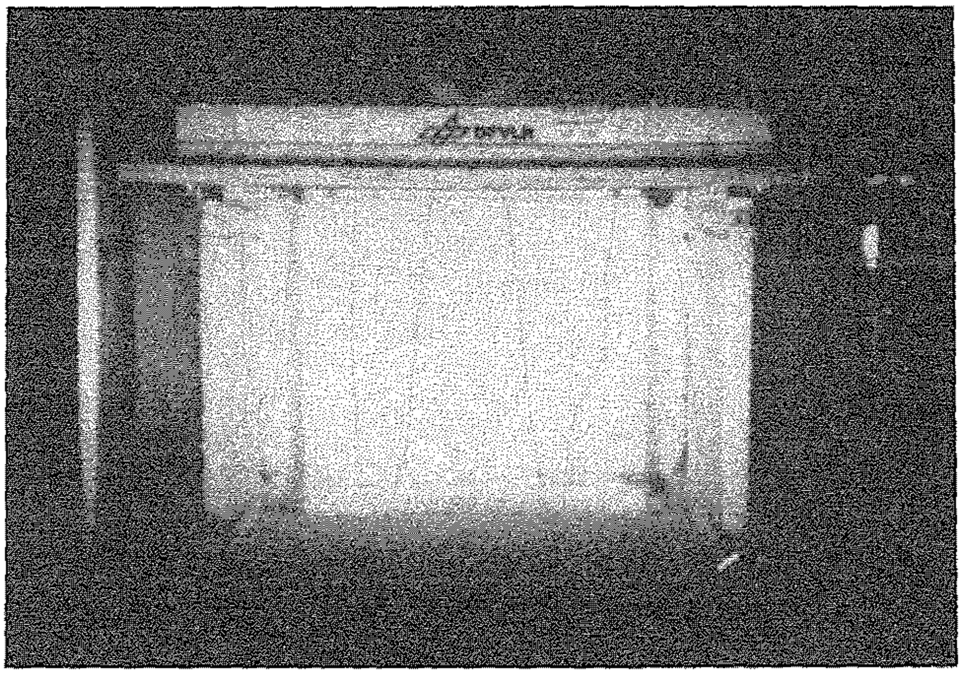

Figure 4-10. Slightly Deformed All-Sandwich Specimen

Figuer 4-11. Further Deformed All-Sandwich Specimen

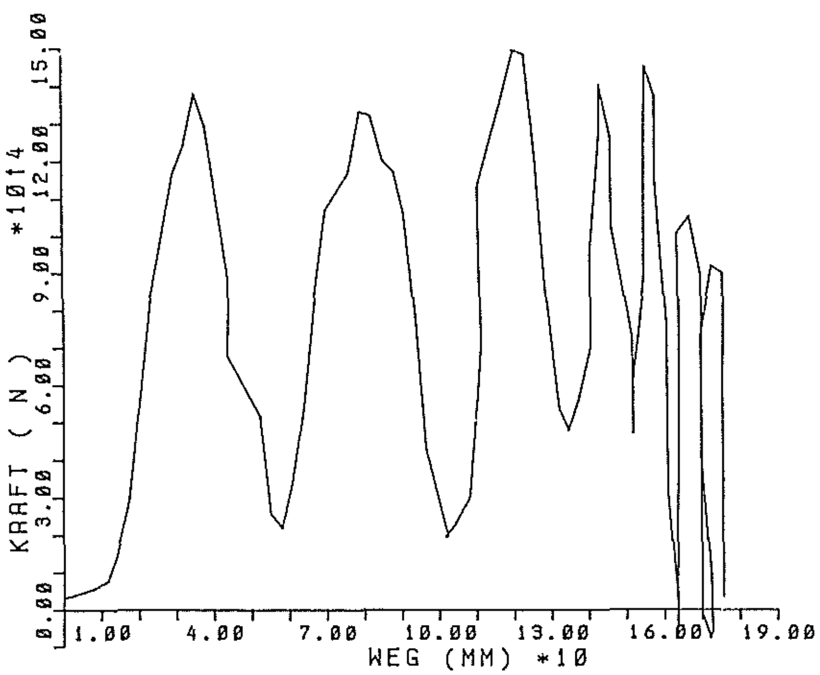

Figure 4-12. Dynamic Load-Stroke Curve of All-Sandwich Specimen

5. NUMERICAL SIMULATION OF SANDWICH SPECIMEN

As described in [5] and [6] the Finite Element program PAM-CRASH proved to be powerful in the application on sheet-stringer structure. A closer study of a possible application on sandwich structure revealed that much less experience is available. Therefore it was decided to start the simulation on small samples parallel to the experimental program. Some iterations in a joint effort of ESI and MBB engineers were necessary to get a realistic simulation of the sandwich behaviour.

This is mainly due to the additional and more complicated failure modes of sandwich and moreover due to the interaction of the structural members face sheets, core and adhesive. Nevertheless the results have been improved significantly. The failure sequence of the specimen without channel sections (see Fig. 4-5, 5-1) as well as with channel sections (see Fig. 4-7, 5-2) are quite similar to the test results.

Furthermore the load time histories are reasonably accurate concerning their characteristic as well as concerning the load levels (Fig. 5-3). All in all these results and the resulting experience are a good basis for future applications e.g. parametric studies on the sample size as well as on full scale components.

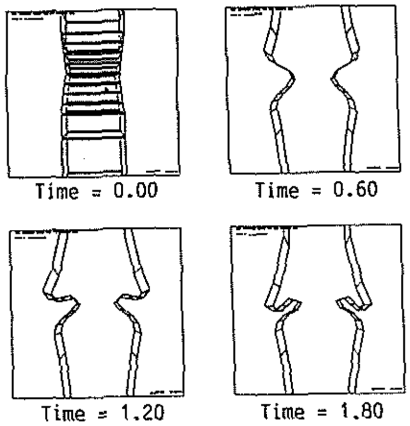

Figure 5-1.
Failure Sequence of
Unreinforced Specimen

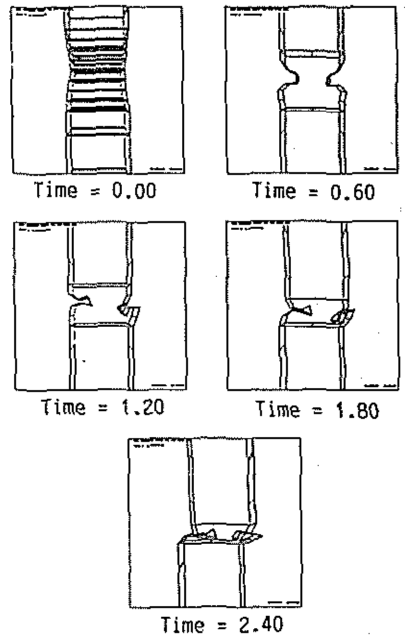

Figure 5-2. Failure Sequence of Reinforced Specimen

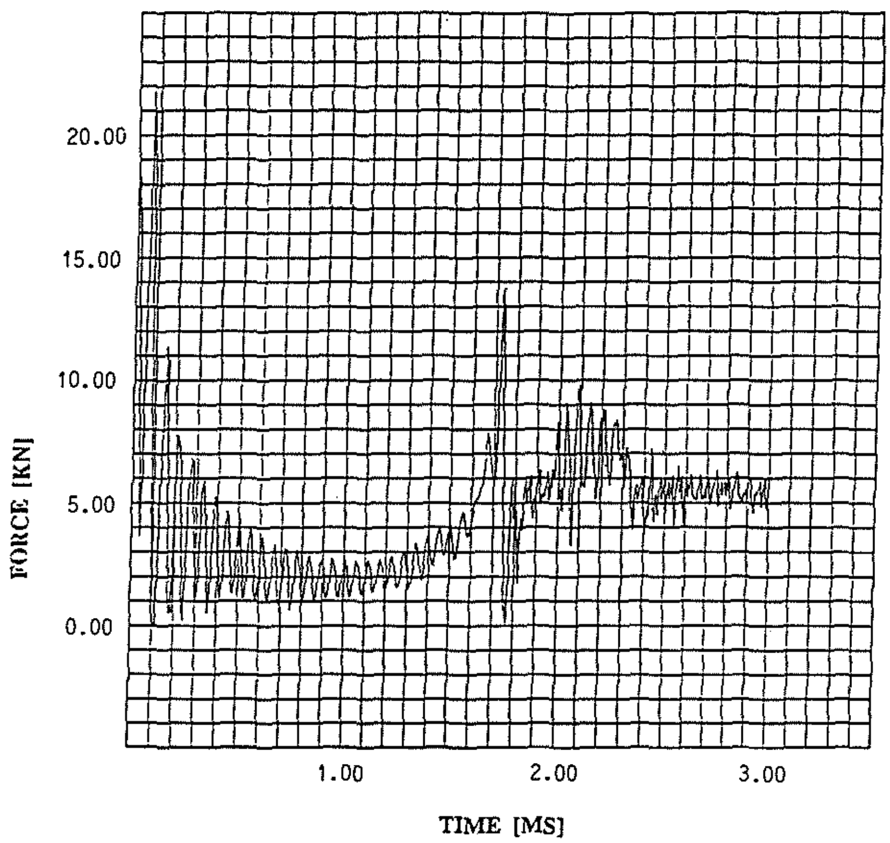

Figure 5-3. Load Time History of Numerical Simulation

6. COMPARISON OF THE CRUSHING BEHAVIOUR OF STRUCTURES

6.1 Small Sandwich Specimen

Although these small sandwich specimen represent only a small detail of a real helicopter subfloor structure it is worth to compare the static and dynamic behaviour of these specimen with inward beads and enclosed channel sections (see Fig. 6-1).

It can be seen that the static tests yielded significant scatter in the results (lower $E/\bar{m}$ for Nomex core and higher $E/\bar{m}$ for Al-core). The same two core types were investigated in the dynamic tests but the results are nearly constant. The same tendency was found in the comparison of static and dynamic tests of sheet-stringer panels [5] . Our conclusion is that under dynamic load all kinds of lightweight structures are less sensitive to inperfections and to instability failure than under static load.

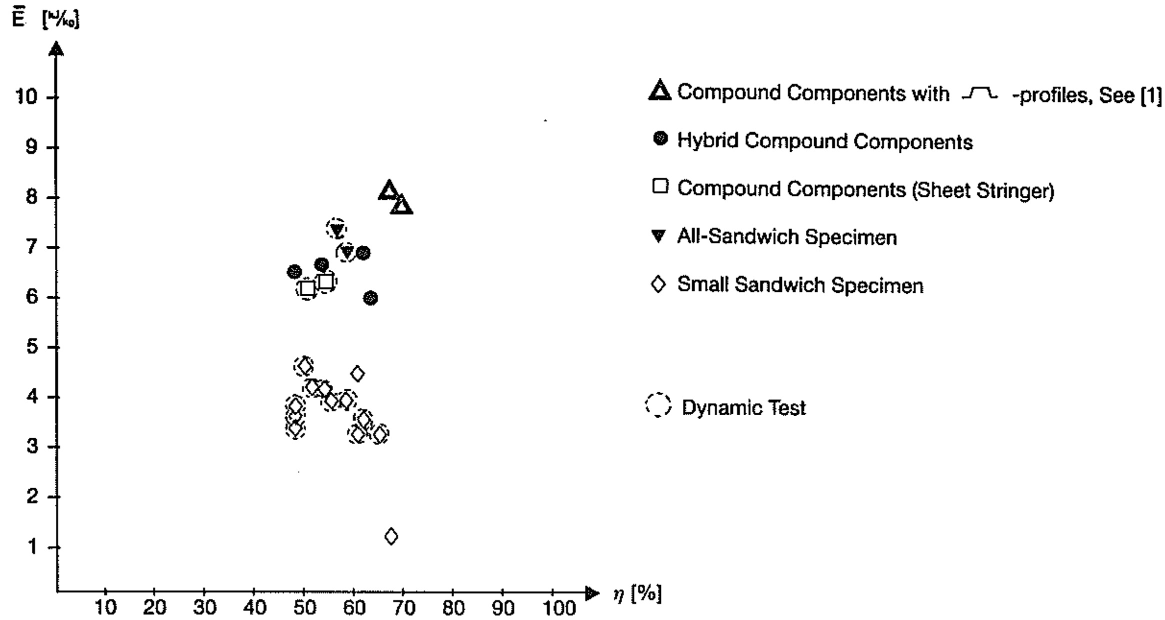

Figure 6-1. Specific Energy Absorption and Efficiency of Various Specimens

6.2 Metallic Subfloor Structures

In this chapter the crushing behaviour of altogether ten specimens shall be compared which represent due to their size and their construction (see chapter 4.2) real helicopter subfloor structures. All of them had a H-shaped cross-section. In addition to specimens which were already presented in [5] and the specimens of which the development was described in chapter 4 also the results of sheet-stringer components which were drop-tested in the meantime shall be included in that comparison. The specimens were in particular:

- two sheet-stringer specimens under quasistatic load

- four hybrid (sheet-stringer/sandwich) specimens under quasistatic load

- two sheet-stringer specimens under dynamic load

- two all-sandwich specimens under dynamic load

The results of the first two specimens were already presented in [5] (see also Fig. 6-1). They were quite promising in respect of efficiency and specific energy absorption. Also the static results of the hybrid specimens fit quite well into the diagram (Fig. 6-1) especially if it is considered that the sandwich parts of these specimens were not as optimized as the sheet-stringer part. The good efficiency of such a specimen can be seen too on the load stroke curve (Fig. 6-2).

The load-stroke curves of the dynamic tests with sheet-stringer specimens (Fig. 6-3) showed a very comparable characteristic as the all-sandwich components (Fig. 4-12) but on a lower load level resulting in a bigger stroke. To our surprise the efficiency is with 51 ÷ 59% lower than from the static tests contradicting our hitherto existing experience that dynamic tests yield a more stable behaviour. The reason seems to be that the dynamic overshoot creates high but very short load peaks which directly influence the efficiency (see chapter 2). But it is very doubtful that such short load peaks impair the dynamic behaviour of the total helicopter at all. Taking this into account the efficiency is probably in the order of 65 ÷ 70%. Nevertheless by watching the high-speed films e.g. the panel connections (for both types of specimens) and the sheet/stringer connections can be identified as areas of potentail improvements as the connections seperate partly. But especially for the sheet-stringer specimens this seperation shouldn't be overestimated because the planed stroke (130 ÷ 150 mm) of these specimens was exceeded by far due to too heavy drop masses. On the other hand the energy absorption capability of the sandwich specimens was better than expected. In addition they yielded a higher load level at smaller strokes (Fig. 6-3, Fig. 4-12) although the four dynamically tested specimens were of comparable size. Finally an inspection of all specimens after the drop test showed that the sheet-stringer components maintained a better structural integrity which is very desirable (Fig. 6-4 and Fig. 6-5) to cope with secondary impacts.

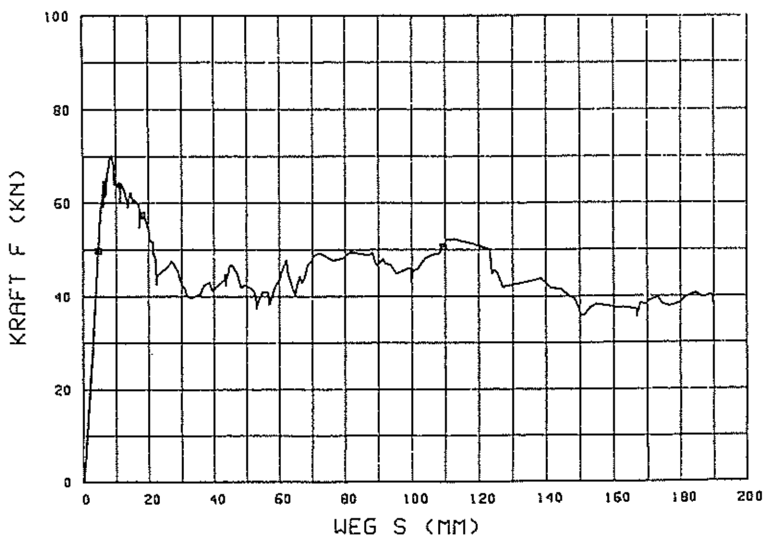

Figure 6-2.

Static Load-Stroke

Curve of Hybrid Specimen

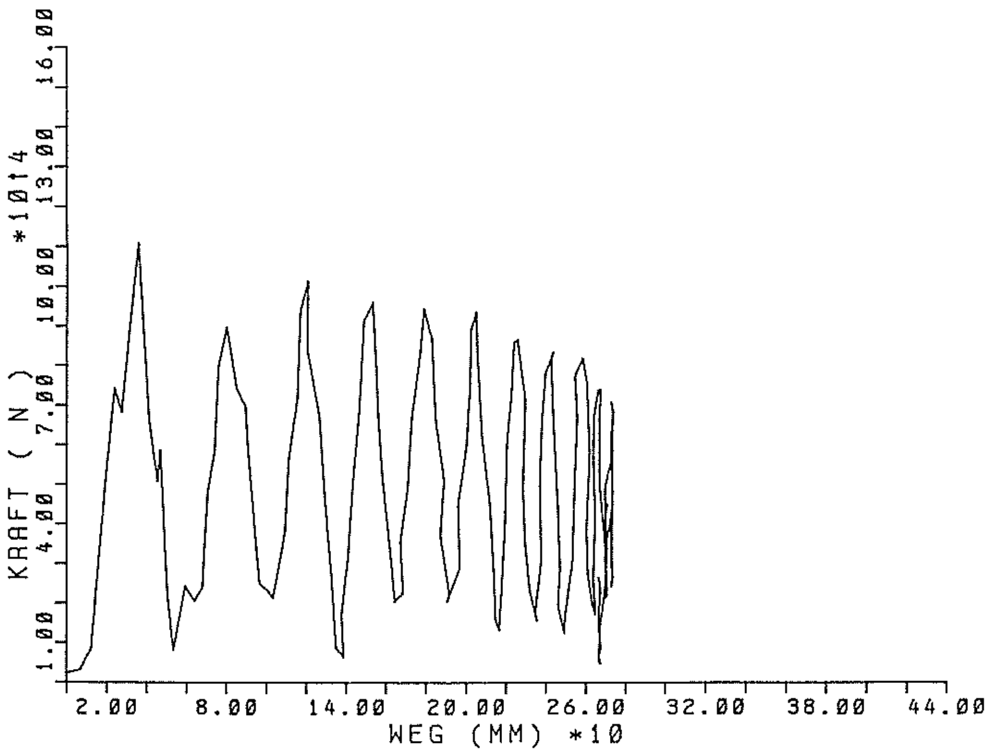

Figure 6-3. Dynamic Load-Stroke Curve of Sheet-Stringer Specimen

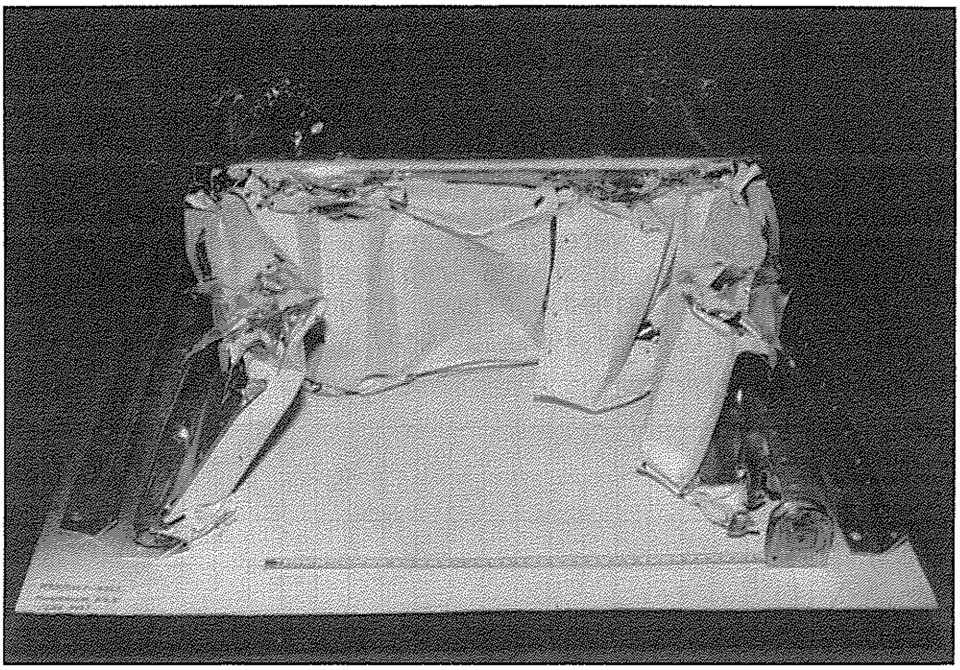

Figure 6-4. Sheet Stringer Specimen after Drop Test

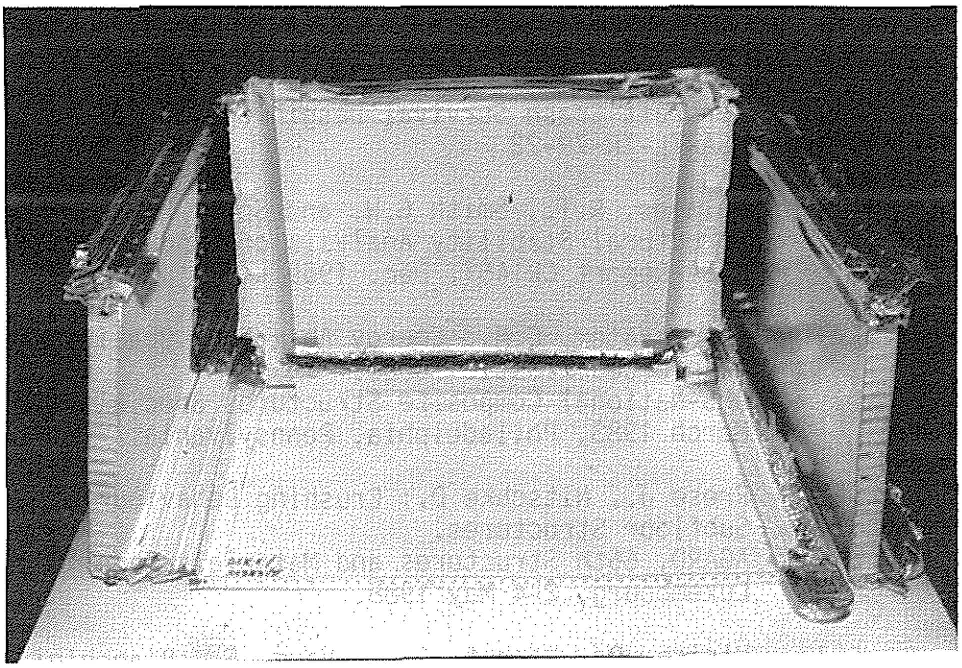

Figure 6-5. All-Sandwich Specimen after Drop Test

7. CONCLUSIONS

This program has been performed to investigate and optimize the crashworthiness of metal sandwich structure. All constraints arizing in a real structural application have been considered. Max. attention has been put on the topic to have a weight optimized structure considering not only the crash requirements but also the load envelope of underflorr structure with fuel tanks in flight operation.

With some helpful information from former investigations at MBB it was possible to develope suitable trigger and tuning devices which improved the basically poor behaviour of metal sandwich concerning energy absorption drastically. The specific energy absorption is very comparable to an optimized sheet stringer structure as well as the efficiency which was reached. The higher tendency of sandwich structure to structural desintegration after the intended stroke may be compensated if the sandwich is carefully integrated in a sheet-stringer environment.

8. REFERENCES

[1] Bruhn, E.F.: Analysis and Design of Flight Vehicle Structures.
Jacobs Publishing Inc.

[2] Aircraft Crash Survival Desgin Guide, Vol. I-V, USARTL-TR-79-22

[3] Sullins, R.T., Smith G.W. and Spier E.E.: Manual for Structural Stability Analysis of Sandwich Plates and Shells.
NASA-Report CR1457, Dec. 1969

[4] Kindervater, C.M.: Energy Absorbing Qualities of Fiber Reinforced Plastic Tubes.
AHS-National Composite Structures Specialist's Meeting, March 1983, Philadelphia, Pennsylvania.

[5] Frese J., Nitschke D.: Crushing Behaviour of Helicopter Subfloor Structures.
AGARD, 66th Structures and Materials Panel Meeting, Luxembourg, 2-4 May 1988.

[6] Ulrich, D., Picket, A.K., Haug, E., Bianchini, J.: Crashsimulation and Verification for Metallic, Sandwich and Laminate Structures.
AGARD, 66th Structures and Material Panel Meeting, Luxembourg.

[7] Chedmail, J.F., Du Bois, P.: Numerical Techniques, Experimental Validation and Industrial Applications of Structural Impact and Crashworthiness Analysis with Supercomputer for the Automotive Industries.

[8] Hicks, J.E.: Economic Benefits of Utility Aircraft Crashworthiness, USAAAVS Technical Report 76-2.
U.S. Army Agency for Aviation Safety, Fort Rucker, Alabama, July 1976.