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DAMAGE TOLERANCE ASPECTS OF LAUNCHER UPPER STAGE COMPOSITE STRUCTURES

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Zusammenfassung

In launchers, composite sandwich structures are often the preferred designs for non-pressurised primary structures due to their advantages compared to metallic structures (i.e. lightweight structure with high stiffness and high buckling capacity). For flight readiness, each composite structure shall be qualified. The qualification process covers global and local verification including material testing, structural and dynamical analysis, damage tolerance analysis and full-scale testing.

The damage tolerance of composite structure including non-destructive inspection is then a critical aspect in the justification of new sandwich structure. Damage tolerance aspects are considered early in the development phases in order to increase the structure robustness. The fracture control requirements specific to composite structures will first be shortly presented; the requirements are derived mainly from two standards: an in-house design requirements applicable document and ECSS-E-ST-32-01C standard which serves as reference document.

An example of justification with respect to fracture control will then be presented for an advanced composite primary structure. Various types of defects were investigated: delamination, hole which conservatively simulates defects affecting the thickness of the skin and mechanical impact. The present paper focuses however on low velocity mechanical impact because of its criticality in terms of detectability. The justification relies on test only. Destructive and non-destructive tests were performed to assess the degradation of the structure containing damage.

1. INTRODUCTION

In launcher engineering, the use of composite structures has increased over the last decades due to their many advantages: light weight structures, good resistance to fatigue, with high stiffness and high buckling capacity.

However, few drawbacks of composite material shall be mentioned: poor resistance to lightning, high sensitivity especially in compression to various types of defect including in particular delamination or low velocity mechanical impact. In space industry, the low velocity impact results mostly from tool drop during manufacturing and integration. This kind of defect is particular critical because the damage is not visible on the top surface of the material and requires intensive inspection to be detected. The defect detectability is even more critical for sandwich structure with carbon fibre reinforced skin than for monolithic structures.

Despite of these negative issues, for launcher non-pressurised primary structures, composite material is preferred. The material choice is often a composite sandwich which proposes mass saving associated with high stiffness and high buckling resistance. As secondary advantages, composite sandwich shows good thermal and acoustic insulation behaviour. The sandwich structures are often made of carbon fibre reinforced facesheets bonded to an aluminum honeycomb core.

However, the qualification of such structures is quite challenging, the structure is either highly loaded or are submitted to high temperature which questiones the integrity of the material.

After a quick presentation of the various steps involved in the qualification of a launcher composite structure, emphasis will be given to the damage tolerance aspects. First the requirements with respect to damage tolerance will be described and then an example of the damage tolerance justification of an advanced composite primary structure of Ariane 5 upper composite will be given.

2. QUALIFICATION OF COMPOSITE STRUCTURE FOR CIVIL LAUNCHER

In launcher development, each new primary structure is qualified considering the following aspects. Material characterization, strength verification, dynamic environment qualification (specially when electrical or fluid control relevant equipments are mounted on to the primary structure), damage tolerance principles and full scale testing in flight representative thermal environment.

The qualification requirements are listed in an Ariane 5 applicable document [1]. This document was established in collaboration between CNES, SNECMA and Astrium Space Transportation. Prime and sub-contracting company shall comply to such requirements.

2.1. Material Characterization

The composite material shall be characterized at unidirectional level but also at sub-component level including both multidirectional laminate and sandwich level. This is done on representative test coupons. The characterization shall also account for the environment (temperature, humidity…) seen by the structure considering integration, transportation and launch phases.
The various tests allow to derive the material strength allowables required for further qualification steps (e.g. determination of margin of safety).

The high loaded sandwiches are connected to metallic rings to allow load transfer to adjacent structures. Due to the complexity of such interface in terms of load path and numerous potential failure modes, the load carrying capability can be determined using finite element calculation but required to be correlated by testing. The FE-analyses are also used for prediction prior to testing to place the measurement points.

The steps sketched above shall be repeated for each new composite sandwich structures due to its singularity and in order to guarantee the high level of reliability needed in the space business. A drawback of such approach is the resulting extensive test program in terms of budget and time.

2.2. Strength verification

The qualification of a composite structure with respect to strength follows the logic sketched in Figure 1. The example is based on a recent development.

The strength qualification consists of both a global and a local verification. Few inputs are needed to start the strength qualification loop: design, material data and loading.
A preliminary design proposed in the first phase is optimized during the qualification of the structure.

A clear load status shall be given to be used during the entire dimensioning loop. The loads shall be given flight phase consistent. The loads consist of:

- General mechanical loads coming from booster induced loads (static and dynamical accelerations), engine induced loads (static and dynamical accelerations), global aerodynamical loads (Wind and Gust), mounting induced loads;
- Pressure loads resulting from the local aerodynamic loads and venting pressure,
- Inertia local loads which are the combined static and dynamic accelerations resulting from the local answers of equipments due to dynamic environment (low frequency dynamics, vibro-acoustics, high frequency transient shock event),
- Thermal loads which results from the launcher trajectory as well as the temperature of the adjacent structures like cryogenic tanks.

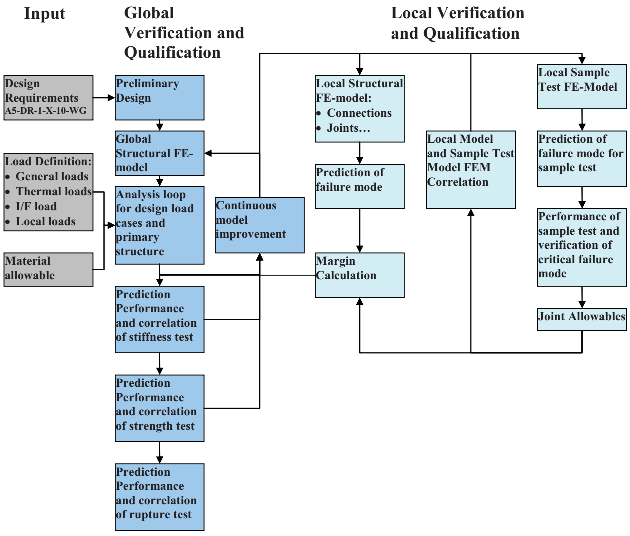


FIGURE 1. Strength verification development logic for a composite structure

The global verification consists of a finite element analysis of the entire structure. In the local verification, special design features as joints; cut-outs, inserts and lay-up transitions are investigated in details and correlated with the test results made at component level.

2.3. Dynamic environment validation

The dynamic environment validation is part of the system of stage qualification. The performed tests are mainly modal survey tests to validate the dynamic models and requirements in terms of stiffness and modal data basis. Other type dynamics tests (random, acoustic, etc) are performed to validate those models which are used to derive the local dynamic environment of possible equipments. In some cases also pyrotechnic separation tests are performed to derive the shock propagation and validate the models and consequently the shock sensitive equipments.

2.4. Damage tolerance principles

Damage tolerance principles should be implemented at the beginning of the development programme to avoid an unfavorable design and "bad" surprises during the qualification. Indeed wrong design could result in delamination initiation. Examples of delamination onsets are given in Figure 2.

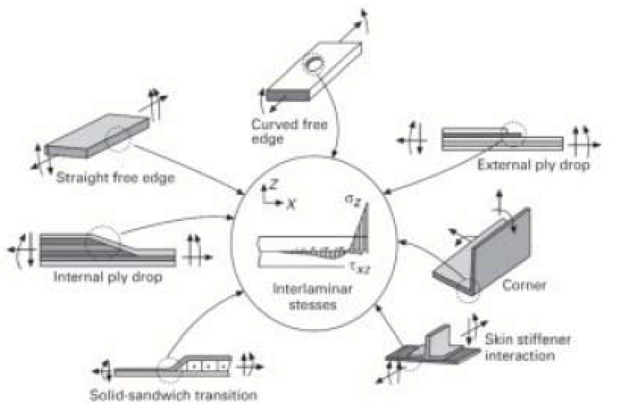


FIGURE 2. Delamination onset due to geometry [6]

Details on the damage tolerance requirements and justifications will be given in the next two chapters.

2.5. Full scale testing

One of the last step of the qualification of a new structure consists of the full scale test. A flight representative hardware is tested in flight representative environment (temperature, dimensioning load case, adjacent structures…). Tests are performed to asses the stiffness, correlate the global analysis model and determine the load carrying capability of the structure. The structure shall be able to withstand without degradation the dimensioning load multiplied by a factor of 1.25. After exploitation of the previous full scale testing, the structure is tested until rupture. The full scale testing is accompanied by another extensive numerical work in order

- first to predict the tests also to benefit fully from the test results by introducing for example the measurement points on the critical location,
- Secondly to validate and correlate the global finite element verification.

3. DAMAGE TOLERANCE REQUIREMENTS

Composite material parts; whose failure leads to catastrophic or major events, including loss of mission; shall be qualified according to damage tolerance principles. A structural screening shall be performed to classify the fracture control items. The classification is described in Section 3.1.

The structural integrity of the structure shall remain in the presence of undetected defects as well as in the various environments seen by the structure.

The type of defects which could occur to a composite structure can be classified in three groups:

- Manufacturing defects: Manufacturing defects can take place during the entire manufacturing process including lamination & cure cycle as well as bonding steps. Examples of manufacturing defects are: fibre waviness, porosity, contaminations due to backing paper or plastic liner…. Machining of hole could also lead to delamination formation
- Defects due to a "bad" design: Delamination could start due to a non-suitable design, see Figure 2
- Mechanical impact damage resulting from a mechanical threat to the structure e.g. tool drop. For mechanical impact, two approaches can be followed: BVID or ULID.
  - The BVID approach or Barely Visible Impact Damage size approach ensures that the structure is damage tolerant after a mechanical impact producing a damage which is without inspection means not visible. The BVID is determined for each structure, material type and lay-up configuration by tests: sound coupons are impacted at various energies and the damage is estimated mostly in terms of dent depth and damage size. The residual strength capability of the structure/component is then estimated also by tests for coupon containing barely visible impact damage.
  - The ULID approach or Upper Level of Impact Damage energy approach ensures that the structure/component is damage tolerant after being impacted by the worst possible potential mechanical impact. A risk analysis is performed in order to estimate the impact energy associated to the worst impact threat. Based on this impact, the residual strength of the structure/component is then experimentally determined. If the structure strength cannot be guarantee with such associated energy, the energy shall be reduced and a protection shall be envisaged to ensure that such energy is not overstepped.

For carbon fibre reinforced sandwich structures, the BVID approach is favoured because the dent depth increases dramatically even for low impact energies as shown in figure 3.

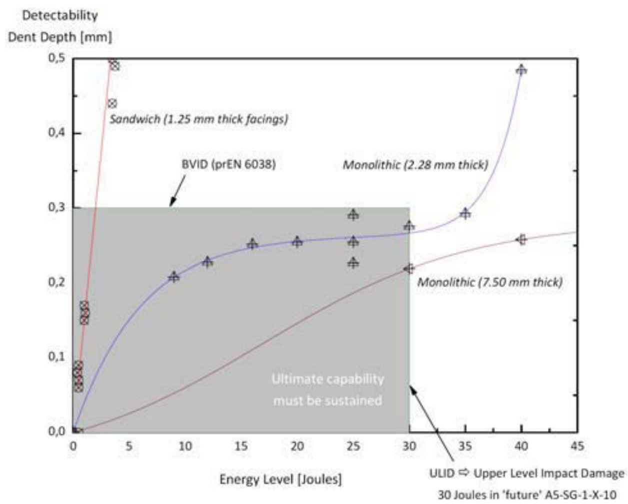


FIGURE 3. Damage domains taken from [5]

The list of defects is then exhaustive and is function of the manufacturing route. The most probable defects which could occur and the most critical ones shall be identified for each structure in a case by case analysis in order to establish the damage tolerance justification logic. The risk analysis shall consider the type of composite system, the type of raw material (prepreg…), the manufacturing process, the integration process, the transportation means. The result of the risk assessment is then the basis to define which defects will be idealized and tested. The inspection method and detectabilty limit serve to define the defects size.

3.1. Classification of structural parts

As per ECSS standard [3], the Ariane 5 requirements document [1] requires that all structural parts shall be examined to determine its damage tolerance classification. Identical classification as per ECSS classification is considered: the structural parts are classified as exempt, low risk, fail safe or safe life.

3.1.1. Exempt items

Exempt items are either:

- parts whose failure does not lead to catastrophic or major events, or
- standardized items (with the exception of screws) or items qualified through extensive test program and rigorous process control during production.

3.1.2. Low risk parts

Low risk parts shall meet the following requirements:

- The structures shall not be a pressurized hardware,
- The part shall not include structural bonded areas,
- At the limit load, the stress is below the damage tolerance threshold stress. In the absence of representative values, it can be considered that the stress is below the damage tolerance threshold stress when the following criteria are met:
  - at the limit load the maximum tensile stress taking into account the stress concentration factor is lower than 40 % of the material ultimate capability in the conditions of use (temperature, ageing, humidity), and
  - at the limit load the maximum compressive stress taking into account the stress concentration factor is lower than 25 % of the material ultimate capability in the conditions of use (temperature, ageing, humidity)
- In addition to NDI during manufacturing, the part receives a close visual inspection covering 100% of the surface to detect relevant impact damages.

3.1.3. Fail safe items

These are structural parts or connections with multiple load paths. Fail safe parts shall meet the following requirements:

- After the elimination of the load path which in case of failure leads to the highest load in the remaining path, the structure shall sustain the redistributed limit loads with a factor of safety 1,15 for composite items, with respect to strength and safety requirements. The resulting modification of the dynamic behaviour shall be assessed and taken into account.
- The failure of the item shall not result in the release of any part or fragment which results in an event having catastrophic or major consequences
- A fatigue analysis of the remaining load path shall show positive margin. The fatigue analysis shall be based on tests. The fatigue verification shall consider at least situation when number of cycles and level of load exceed the simplified figures below:
  - 10 cycles reaching 70% of the material strength,
  - 100 cycles at reaching 60% of the material strength,
  - 1000 cycles reaching 50% of the material strength
- It shall be verified that dynamic or transient analysis used to derive load spectra for nominal situation are still applicable for the remaining structure in fail safe conditions

3.1.4. Safe life Items

In safe life item, both manufacturing defects and those resulting from mechanical threat shall be investigated.

- Manufacturing defects: for each safe life structural part, a list of potential manufacturing defects shall be established and acceptance criteria derived. The worst defects in the part shall not grow within the design service life and shall be able to sustain the design ultimate load at the end of the design service life.
  The design life is the service life multiplied by a life factor of 1 and a load enhancement factor of 1.15 on the alternating load. The service life shall consider all the events seen by the structure including handling, transportation, ground loads and launch: lift-off, booster flight, lower stage flight and upper stage flight. The maximum acceptable defect size which also depends on the local stress state in the structure shall be detected by non-destructive method.

- Mechanical impact: A risk analysis shall be performed to identify the threats to the structure as well as the Upper Level of Impact Damage (ULID) that can occur to the structure. If this risk analysis cannot be performed, 30J shall be used for ULID. However, for sandwich structure, the BVID approach, described above, is preferred. Based on representative tests, it shall be demonstrated that the structure can withstand the required combined mechanical and thermal loads (both static and fatigue) considering the damage produced. As for manufacturing defects, the damage shall not grow within the design life and shall sustain the ultimate load at the end of the design life.

- Non destructive inspection means shall ensure that the critical manufacturing and mechanical damage can be detected with 90% probability level and 95% confidence level. The inspection capability shall be demonstrated for each type of structure and each defect type by testing on representative coupons containing induced defect/damage. The same inspection method and tool is then used to inspect the flight hardware after manufacturing.

Most of the structures developed for launcher application are classified either as fail safe for the interfaces or as safe life for the main panel.

4. DAMAGE TOLERANCE JUSTIFICATION

The qualification of a launcher composite structure with respect to damage tolerance relies on tests only as the numerical tools existing today remains at academic level and the qualification of the hardware require anyway numerical methods which are validated by test. Therefore for each type of structures, many tests are required to justify the different types and sizes of defects, different loading conditions, and different environments.

However, during launcher development program, due to programmatic reasons compromise have to be found to justify the damage tolerance. Therefore in the past developments, only the most critical types of defect with respect to residual strength were analysed, namely:

- hole: which symbolized in a conservative way all defects affecting the fibre,
- delamination/debonding: which represent any non-adherent plies,
- low velocity mechanical impact.

The present paper emphasises the mechanical impact justification of an Ariane 5 upper stage sandwich composite structure.
The sandwich structure consists of CFRP facesheets glued to an aluminium honeycomb. The facesheets are made of high strength carbon fibre embedded in a tough epoxy resin. The raw material is delivered as prepreg. The facesheets are manufactured using fibre placement technique which ensures high process reliability and a good quality.

The objectives of the test campaign were to:

- Determine the Barely Visible Impact Damage (BVID) for this type of structure,
- Determine the residual strength after impact for the impact energy associated to the BVID.

4.1. Test Procedure

4.1.1. Low velocity mechanical impact

To perform the mechanical impact test, the device used consists of a drop weight impact tower, see Figure 4. A hemispherical impactor is mounted on the tower. The sample to be impacted is fixed in a support fixture as per Figure 5 and placed below the tube containing the impactor. The impact energy is then calculated using the mass of the impactor and the drop height. By modification of the drop height various energies can be achieved. The specimens were impacted with energies in the range [0.5 J - 20 J].

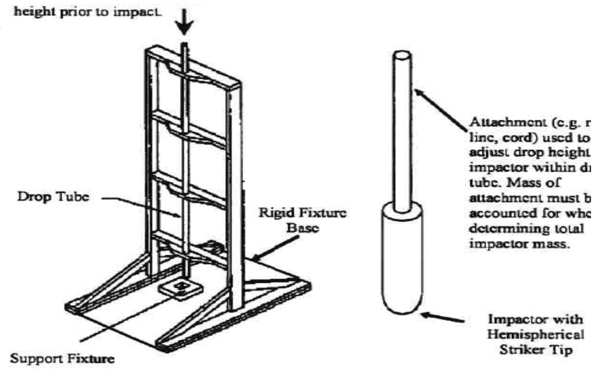


FIGURE 4. Low velocity mechanical impact test device

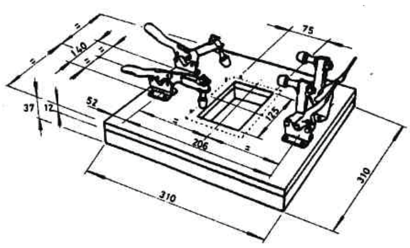


FIGURE 5. Test sample fixture

After mechanical impact, the indentation depth was measured using a depth gauge. Additionally ultrasonic inspection was performed to determine the extend of the damage.

Few samples were cut after mechanical impact in order to identify the damage through the sandwich thickness.

4.1.2. Residual strength after impact

For compression after impact testing, it was decided to test only specimens damaged at 3.5 J impact energy because this energy level results to a damage which is barely visible for the classical structures used in the Ariane 5 Upper Stage family. Non damaged samples were also tested under the same conditions for comparison.

As no international standard exists for sandwich material, the test jig used for laminate, described in ASTM [2] was modified for sandwich structures. The tool is presented in Figure 6. Using this method, no design allowable can be determined as the results depends on geometry of the specimen.

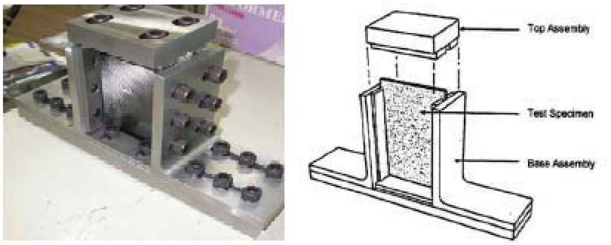


FIGURE 6. Compression after impact testing jig

Two loading conditions were investigated, the samples were loaded either

- statically until final rupture, and
- cyclically according to typical Ariane 5 upper stage load spectrum and then up to final rupture using static load.

4.2. Results

4.2.1. Low velocity mechanical impact

The results of the low velocity impact test are plotted in terms of indent depth versus impact energy in Figure 7. The relationship between impact energy and indent depth is linear for this type of sandwich material.
It is also observed that the damage area in the facesheet increases linearly with the impact energy until reaching a plateau around energy of 5J.

Figure 8 shows the through the thickness damage at three various impact energies: 0.5J, 3.5J and 10J. Delamination and fibre breakage in the skin as well as core crushing, even at low impact energy, are characteristics of the damage in composite sandwich with thin facesheets. From an impact energy of around 3 J, debonding between the facesheet and the core is observed. The facesheet opposite the impact is not damaged.

Sandwich material behaves differently to laminate with respect to impact damage. The damage in the skin is limited in size due to the fact that the honeycomb core absorbs most of the impact energy. Moreover, the impact energy to produce a barely visible damage is much lower in a sandwich coupon than for laminate.

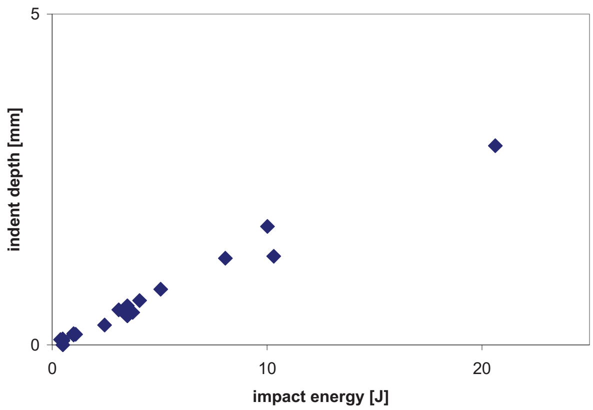


FIGURE 7. Low velocity mechanical impact test results

FIGURE 8. Through the thickness damage for three impact energies (0.5 J, 3.5 J and 10 J)

4.2.2. Residual strength after impact

Figure 9 shows the results of the compression after impact tests. No significant influence of the cyclic loading can be outlined. This result is confirmed by the performed ultrasonic inspection after the cyclic loading. The non-destructive inspection did not show any damage increase. Therefore the difference in results between the cyclic compression tests and the static ones is attributed to standard test result deviation.
Compared to a non-damage specimen, the residual strength of damaged samples (at 3.5J impact energy) is reduced by around 20%.

The failure mode is similar in coupons with or without damage: skin compression and core shear failure

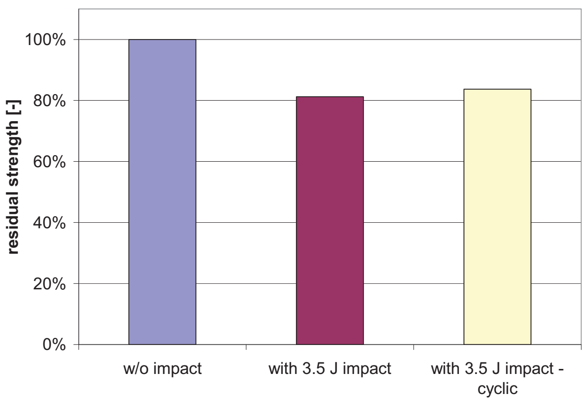
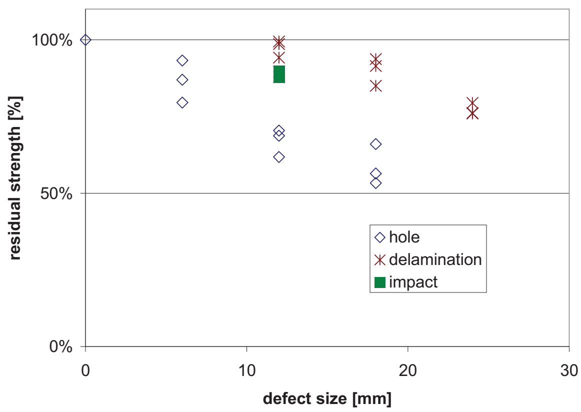


FIGURE 9. Compression after impact test results

In order to compare the influence of the defect type, two impacted specimens at 3.5J were subjected to "standard" edgewise compression test. The residual strength is similar to the one obtained with the compression after impact tool. Figure 10 shows the comparison of the residual strength considering either delamination in one facesheet or open hole or mechanical impact damage.

Similar to the behaviour of a carbon reinforced monolitical composite structure [4], the open holes are the most critical type of damage due to the complex damage state resulting from mechanical impact (various delamination and fibre breakage).



5. CONCLUSION

In launch vehicle, the use of composite material in, particular of carbon fibre reinforced sandwich structure is essential. Therefore their qualification in spite of being challenging should be mastered. The various steps to achieve a successful qualification have been shortly described in the present paper.

Due to the high sensitivity of defects and damage of composite materials, their qualification requires a positive justification with respect to damage tolerance: the structure shall maintain its integrity in presence of non-detected damage. An improved non-destructive inspection method might be necessary to achieve a positive justification.

An example of justification with respect to damage tolerance was presented above. Emphasis was put on low velocity mechanical impacts of a carbon reinforced sandwich structure. For a Barely Visible Impact Damage, the rupture strength was reduced by around 20%.

Such strength reduction cannot be directly considered in the material allowable as this is in contradiction to the need of structure optimization. However such knowledge is mandatory to treat any incidents and/or process deviation.

6. REFERENCE

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