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Residual strength of stiffened GLARE structures

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Residual strength of stiffened GLARE structures

In existing design methods for stiffened panels, no distinction is made between large cracks caused by fatigue and large cracks from impact damage after uncontained engine disintegration. Although large fatigue cracks are not an issue in GLARE structures, damage from uncontained engine disintegration will be.

An experimental study has been made on the effectiveness of riveted and bonded GLARE-2 stringers across a crack, compared to Al 2024-T3 stringers. The riveted GLARE-2 and Al 2024-T3 stringers were found to have an almost equal failure load. The GLARE-2 stringers was 28% lighter than the Al 2024-T3 stringer. The bonded GLARE-2 and Al 2024-T3 stringer were found to have respectively a 77% and 19% higher failure load.

A finite element analysis showed that the strain hardening of GLARE 2 can be taken into account to predict the failure load of the stringers. After modifying the governing equations in the displacement compatibility method as used e.g. by Swift, also in this method the strain hardening of GLARE 2 can be incorporated.

In a residual strength analysis, both stringer failure and skin failure are taken into account. Since for a GLARE-3 skin fracture from an initial through crack can be described with an R-curve, the residual strength of GLARE structures can be analysed with existing design methods.
In existing design methods for stiffened panels, no distinction is made between large cracks caused by fatigue and large cracks from impact damage after uncontained engine disintegration. Although large fatigue cracks are not an issue in GLARE structures, damage from uncontained engine disintegration will be.

In an aircraft, uncontained engine failure can cause through-cracks in the centre section of the fuselage. As part of a study on the residual strength of a GLARE structure with such through-cracks, experiments were performed on the fracture toughness of a GLARE 3 skin and the crack arresting capabilities of GLARE 2 stringers.
Occurrence of through-cracks in a GLARE fuselage

In the centre section of the fuselage, through-cracks can be caused by uncontained engine disintegration. They require a residual strength study in a GLARE fuselage.
Fracture toughness of GLARE 3

To test the fracture toughness of a GLARE 3 skin, experiments were performed on unstiffened panels with saw-cuts. The largest panel was 800 mm wide. The initial length of the saw-cut varied. From these experiments, the R-curve appeared to be a valid method to predict fracture propagation in GLARE 3.
R-curves for through-cracks in Al 2024-T3 and GLARE 3

Stress intensity factor $K_R$ [MPa$\sqrt{m}$]

- GLARE 3-3/2-0.3
- Al 2024-T3 Clad

Preliminary data

Crack extension $\Delta a$ [mm]
Crack arrest from GLARE 2 stringers

To test the crack arresting capabilities of GLARE 2 stringers, experiments were performed on stringers attached to a narrow skin strip with a saw-cut over its entire width. Both the strength and the stiffness of the stringers were measured. Three designs were tested. The Al 2024-T3 and the GLARE 2 stringer were tested in both a riveted and a bonded version.
Design of the test specimen to test stringer failure across a through-crack

<table>
<thead>
<tr>
<th>Stringer</th>
<th>Thickness [mm]</th>
<th>Cross section [mm²]</th>
<th>Weight per unit length [kg/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al 2024-T3 Clad</td>
<td>1.0</td>
<td>61.6</td>
<td>0.165</td>
</tr>
<tr>
<td>Al 7075-T6 Clad</td>
<td>1.0</td>
<td>61.0</td>
<td>0.162</td>
</tr>
<tr>
<td>GLARE 2-2/1-0.3</td>
<td>0.85</td>
<td>51.3</td>
<td>0.118</td>
</tr>
</tbody>
</table>

Narrow skin strip
Opening
Saw-cut
Stringer
Strength of the stringers

The riveted GLARE 2 stringer had a slightly higher failure load than the riveted Al 2024-T3 stringer. Per unit weight, the GLARE 2 stringer was 32% stronger than the Al 2024-T3 stringer and 13% stronger than the Al 7075-T6 stringer.

The bonded GLARE 2 stringer was by far the strongest, even without taking into account the weight reduction.

Per unit weight, the riveted GLARE 2 stringer was 19% stronger than the bonded Al 2024-T3 stringer.
Actual failure load and failure load per unit weight of the stringers

Failure load per unit weight [%]

0  50  100  150  200

Actual failure load [kN]

0  10  20  30  40

Al 2024-T3, riveted
Al 7075-T6, riveted
GLARE 2-2/1-0.3, riveted
Al 2024-T3, bonded
GLARE 2-2/1-0.3, bonded
Stiffness of the stringers

In a stiffened panel, sufficient stiffness of the stringers is required to arrest the crack in the skin. In the present experiments, the stiffness of the stringers was defined as the amount of opening of the saw-cut as a function of the load on the stringer.

The stiffness was defined in two ways. For low loads, the initial stiffness is determined by the elastic properties of the stiffener material. At higher loads, the plastic deformations in the stringer result in a reduced effective stiffness. The effective stiffness is expected to control crack arrest in stiffened panels, not the initial stiffness.
Comparison of the stiffness

The initial and effective stiffness of the stringers have been derived per unit weight of the stringer. Per unit weight, the riveted GLARE 2 stringer has a larger initial stiffness than the riveted Al 2024-T3 stringer. At an opening of the saw cut of 1.5 mm, the GLARE 2 stringer had a 33% higher effective stiffness per unit weight, compared to the riveted Al 2024-T3 stringer.

The bonded GLARE 2 stringer had the highest effective stiffness.
Initial and effective stiffness per unit weight of the stringers

Initial stiffness per unit weight [%]

0  50  100  150

- Al 2024-T3, riveted (Experiment)
- Al 2024-T3, riveted (Analysis)
- Al 7075-T6, riveted (Analysis)
- GLARE 2-2/1-0.3, riveted (Analysis)
- Al 2024-T3, bonded (Experiment)
- GLARE 2-2/1-0.3, bonded (Experiment)

Effective stiffness per unit weight, at $\Delta v = 1.5$ mm [%]
Strain hardening in GLARE 2

The riveted GLARE 2 stringer showed less reduction in stiffness at higher loads than the riveted Al 2024-T3 stringer. The reduction in stiffness is linked to the plastic deformations in the stringer. In a GLARE 2 stringer, the material retains a considerable amount of stiffness after yield.
Typical stress-strain curves for GLARE 2-2/1-0.3 and Al 2024-T3
Failure model of a riveted stringer

Besides testing, also an attempt was made to predict the failure load of a riveted stringer in a finite element model. In a riveted stringer, the riveted flange will yield before the other flanges due to the smaller nett-section next to the rivet holes. In a finite element model, each flange can be defined with its own material properties. The effective material properties of the riveted flange can be obtained from a test on a strip with rivet holes. The strain at which this strip fails can be used to predict the failure load of the stringer.
Finite element prediction of failure of a riveted stringer

**Strip tests**
Effective stress-strain curve for flange with rivet holes, obtained from experiments on strips with rivet holes

**Failure model**
Riveted flange with effective material properties

**FEM model**
Riveted flange as first beam

**Strip tests**
Normal stress-strain curve for flanges without rivet holes

Other flanges with normal material properties

Other flanges as second beam
FEM model of the riveted stringers

For the riveted Al 2024-T3 stringer, both the stiffness and the failure load were predicted well. For the GLARE 2 stringer, the failure load was predicted within an error margin of 10%.

Because the predicted stiffness for the riveted Al 2024-T3 stringer compared well to the experimental results, it is expected that also for the Al 7075-T6 and the GLARE 2 stringer the stiffness has been derived accurately.
FEM prediction of the load on the stringers as a function of the opening of the saw-cut

- FEM analysis of the riveted GLARE 2 stringer
- FEM analysis of the riveted Al 2024-T3 stringer
- Experiment on the riveted Al 2024-T3 stringer
- Experiment on the bonded GLARE 2 stringer

Stringer load [kN]

Opening of the skin cut $\Delta v$ [mm]
Designing with strain hardening

The strain hardening in GLARE 2 has a beneficial influence on the residual strength of a stiffened panel. When the strain hardening is ignored, the residual strength will be underestimated.

For a panel with GLARE 2 and Al 2024-T3 strips, the stress intensity has been evaluated using a modified version of the displacement compatibility method.

For the panel with GLARE 2 strips, the stress intensity is overestimated when the strips are assumed to be perfectly plastic. For the panel with Al 2024-T3 strips, the error is negligible.

For GLARE stringers, one should include the strain hardening to obtain an accurate estimate of the residual strength.
Influence of strain-hardening in GLARE 2 strips on the stress intensity in a stiffened panel

Strips either modelled with strain hardening, or as a perfectly plastic strip

GLARE shows a larger error when assuming that the strip is perfectly plastic

<table>
<thead>
<tr>
<th></th>
<th>Skin</th>
<th>Strips per pair</th>
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<tbody>
<tr>
<td>Al 2024-T3</td>
<td>1.6 mm</td>
<td>60 mm²</td>
</tr>
<tr>
<td>GLARE 2</td>
<td>1.4 mm</td>
<td>51 mm²</td>
</tr>
</tbody>
</table>

Panel load per unit width [N/mm]
Acknowledgement

The work described in this study was performed by the Structures and Materials Laboratory of the Faculty of Aerospace Engineering, Delft University of Technology. The work was sponsored by the Structural Laminates Company, manufacturers of GLARE and ARALL. They also provided the material for the GLARE test specimens.

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