Experimental investigation on the water impact behavior of composite structures

R. Borrelli*, M. Ignarra, U. Mercurio
CIRA, Via Maiorise snc, Capua 81041, Italy

Abstract

Within the context of the SMAES European research project funded under the seventh framework programme, an experimental test campaign consisting on drop tests on water was carried out on semi-cylindrical composite structures and it is presented in this work. The main objectives of such test campaign were to improve the knowledge about the water impact behavior of composite structures and to build an experimental database to support the validation of reliable simulation tools to be used during the design and certification process of aircrafts.

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1. Introduction

Impact on water is an event which can be encountered by all aircrafts since many flights happen partly overseas and many airports are located very close to the sea. As shown by the Civil Aviation Authority (CAA) accident investigation report [1], a not negligible percentage of accidents involving helicopters occur on water. With the developments of seaplanes in the early 1930s, the first significant research programs focused on the impact on water started. A 2D analytical estimation of the load acting on a body impacting on water was made in [2]. Such basic analytical work is still the basis of the calculation tools used to estimate the impact force in the pre-development phase of structure susceptible to impact on water.

Nowadays, the certification authorities impose costly requirements to assure a high safety standard for the different aircrafts operating over sea. Ditching analysis is requested for large transport aircraft by airworthiness authorities, e.g. EASA or FAA. The respective requirements are specified under “CS 25.801 Ditching”. They can be briefly summarized as in the following: the aircraft should be able to land on water as safely as possible to float long.

E-mail address: r.borrelli@cira.it

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enough in order to enable the passengers to evacuate. Moreover, the increasing use of composite materials in aerospace applications makes the certification process even more complex, since developing a reliable methodology for fully predicting the performance of composite structures taking into account the several damage mechanisms is a big challenge. Ditching analysis tends to use numerical methods due to manifold reasons [3]. These numerical tools need development and continuous enhancement to cope with the computationally challenges of the problem: highly localized pressure distributions, air cushioning, fluid-structure interaction and hydroelastic coupling, cavitation and ventilation. Research works which testify the relevance of the topic can be found in [4-6].

Within the context of the SMAES European research project funded under the seventh framework programme, an experimental test campaign consisting on drop tests on water was carried out on semi-cylindrical composite structures and it is presented in this work. The main objectives of such test campaign were to improve the knowledge of the water impact behavior of composite structures and to build an experimental database to support the validation of reliable simulation tools to be used during the design and certification process of aircrafts.

The test facility, the test article shape, the impact conditions and the instrumentations were chosen similar to those used for a similar test campaign performed in 2008 on metallic (aluminum and steel) structures [7]. In particular, the test campaign was performed by using the drop tower test facility of the Italian Aerospace Research Centre (CIRA). In order to obtain a complete characterization of the impact event on water, the test articles were instrumented with accelerometers, pressure transducers and strain gages, moreover, high speed cameras were used to record the tests.

2. Drop test campaign

Eight vertical impact tests on water, with different impact velocity and on two different layup configurations, were performed on semi-cylindrical composite structures. In the next sub-sections the test facility, the test articles and the test matrix will be described.

2.1. Test facility

The drop test tower available at CIRA was used for the investigation described in this paper. This facility of the Laboratory for Impact Tests on Aerospace Structures (LISA) consists in an 11.5 m high tower, which is able to guide the descent of a trolley to which the test article is attached. The tower is installed in a corner of the LISA’s pool for water impact test. It is able to perform tests with structures up to 2 tons as weight with a maximum impact velocity of 14 m/s. The required impact velocity $V_i$ is obtained by the free fall of the test article. Given the desired velocity, the drop height ($h$) from the water surface, in absence of any energy loss, would be:

$$h = \frac{V_i^2}{2g}$$

(1)

Fig.1 shows a typical test rig with the test article guided by the trolley at the time of contact with water. Such
picture was captured during one of the test which will be presented in the next sections.

2.2. Test article description and instrumentation

The test article consists of a semi-cylindrical structure (skin) stiffened by three frames holed in the centre and duly located at the lateral sides and in the middle section of the skin as shown in Fig. 2(a) and in the exploded view of Fig. 2(b). The frames are holed in the centre in order to have a test article with geometrical shape similar to that one of an aeronautic structure. The main dimensions of the test article are the following: length (1200 mm), width (950 mm), skin thickness (1.56 mm) and holes diameter (150 mm). The lateral support elements have a rectangular 40 x 7.8 mm section while the two central support elements have a rectangular 20 x 7.8 mm section.

![Fig. 2. (a) composite test article; (b) exploded view.](image)

Skin and frames were bonded by using the adhesive film ST 1035 (STRUCTIL). An additional metal frame (Fig. 2a) with three transversal beams were installed on the free edges on the top side of the test article in order to fix it to the trolley of the CIRA drop tower facility.

Four test articles were manufactured of composite material Hexcel AS4/8552 in two different configurations which are characterized by two different layups for the skin. Two test articles were manufactured in configuration n.1, that is with the following stacking sequence of the skin \([0/90/45/-45/0/90]\), where the 0° direction is the longitudinal one. The remaining two test articles were manufactured in configuration n.2, that is with the following stacking sequence of the skin \([45/-45/0/90/45/-45]\). In all the test articles, the stacking sequence of the frames and of the support elements were \([0/90/45/-45/0/90]\), \([0/90/45/-45/0/90]\), and \([0/90/45/-45/0/90]\), respectively.

The total impacting mass was 198.6 kg which is the sum of the test article weight (10.7 kg), the trolley (150.3 kg), bands, nuts and bolts (16.1 kg) and the metal frame (21.5 kg).

In order to obtain a complete characterization of the impact event on water, the test articles were instrumented with 4 accelerometers, 5 pressure transducers and several strain gages. The accelerometers were located on the rigid frame of the test articles, as shown in Fig. 3a. The pressure transducers were located on the external surface of the skin, as shown in Fig. 3b, where both the distance between P2 and P4 and between P2 and P5 are considered along the arc of the circular surface. Strain gages were installed in the same positions of the pressure transducers but on the inner surface. Data were acquired with a 10kHz sampling frequency.

Finally the tests were recorder by two (for redundancy) high speed cameras at 500 fps both located perpendicularly to the motion and with the framing on the impact area in order to capture the impact sequence.
2.3. Test matrix

Eight tests were performed according to the test matrix in Table 1. In the first column the test identifier is reported. The “real impact velocity” column reports for each test the impact velocity obtained by integrating the 4 acceleration signals and by averaging them. Such value is always lower than the nominal (desired) impact velocity because of the energy losses mainly due to the friction between the trolley and the guides during the fall. The impact velocities calculated from the motion analysis of the high speed movie, indicated at the 6th column, are in good agreement with those ones measured by the accelerometers. The nominal impact velocities of the whole test campaign were chosen with the aim of obtaining for each layup configuration at least three tests characterized respectively by an elastic behavior (no damage), small and localized damage and large damage extension.

The test article TA1 was tested four times. The test DT1 was performed at very low energy in order to verify that the data acquisition system works correctly. The second test on TA1 was performed at a nominal impact velocity of 5.0 m/s. Since non-destructive investigations revealed that no damages occurred after the test, the test article TA1 was tested again at 3.0 m/s (DTR1) and then at 7.0 m/s (DTR2) nominal impact velocities. In this last test, the test article TA1 was irreversibly damaged. In the test DT3, the test article TA2, which has the same skin layup of TA1, was tested under more catastrophic conditions (8 m/s) in order to generate a large damage extension. Three drop tests were performed on the test articles with the layup configuration n.2. In particular, the test article TA3, was tested at 3.0 m/s (DT5) and, since no damage was generated, it was tested again at 7.0 m/s (DT6). The test article TA4, was finally tested at 8.0 m/s (DT7). As shown in Table 1, tests at the same velocity but on two different layup configurations were performed in order to investigate the different behavior with respect to the loads induced by the water impact. All the tests were performed with a nominal attitude equal to zero (vertical impacts).

![Fig. 3. (a) accelerometers; (b) pressure transducers.](image)

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Test article</th>
<th>Configuration n.</th>
<th>Nominal Impact velocity (m/s)</th>
<th>Real Impact velocity (m/s)</th>
<th>Velocity from motion analysis (m/s)</th>
<th>Behaviour</th>
</tr>
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<tr>
<td>DT1</td>
<td>TA1</td>
<td>1</td>
<td>1.0</td>
<td>1.02</td>
<td>Not available</td>
<td>No Fail</td>
</tr>
<tr>
<td>DT2</td>
<td>TA1</td>
<td>1</td>
<td>5.0</td>
<td>4.78</td>
<td>4.79</td>
<td>No Fail</td>
</tr>
<tr>
<td>DTR1</td>
<td>TA1</td>
<td>1</td>
<td>3.0</td>
<td>2.90</td>
<td>2.92</td>
<td>No Fail</td>
</tr>
<tr>
<td>DTR2</td>
<td>TA1</td>
<td>1</td>
<td>7.0</td>
<td>6.59</td>
<td>6.69</td>
<td>Failed</td>
</tr>
<tr>
<td>DT3</td>
<td>TA2</td>
<td>1</td>
<td>8.0</td>
<td>7.70</td>
<td>7.53</td>
<td>Failed</td>
</tr>
<tr>
<td>DT5</td>
<td>TA3</td>
<td>2</td>
<td>3.0</td>
<td>2.94</td>
<td>2.88</td>
<td>No Fail</td>
</tr>
</tbody>
</table>
3. Results

Four acceleration signals were acquired for each test with cfc1000 analog [8] filter at 10khz of frequency sampling. For the data reduction, they were first digitally filtered with a SAE Channel Filter Class (CFC) 60 and then averaged in order to have an unique mean acceleration curve for each test. The mean acceleration curves are reported in Fig. 4a and Fig. 4b for the tests in layup configuration 1 and configuration 2, respectively. As expected, the maximum acceleration peaks (18.5g for the configuration 1 and 22.5g for configuration 2) were obtained for the drop tests carried out at the highest nominal impact velocity (8.0 m/s).

The acceleration peaks of all the water drop tests are compared to each other in Fig. 5. A more rigid behavior was exhibited by the test article manufactured in configuration n.2, as matter of fact, by comparing the tests carried out at the same nominal impact velocity, the peaks obtained with the tests in configuration 2 were found always slightly higher than those ones in configuration 1.

Fig. 4. Mean acceleration (filtered SAE 60) vs. time (a) configuration 1; (b) configuration 2.

Fig. 5. Mean acceleration peaks.
The pressure signals filtered with a SAE Channel Filter Class (CFC) 180 are reported in Fig. 6 for both tests in configuration 1 and in configuration 2. Due to the symmetry, signals measured by the pressure transducer P1 were found very similar to those ones measured by the pressure transducer P3. Indeed, they were both located at the centre of the two bays. Hence, their average curves are reported in the first column of Fig. 6. The same applies for the signals measured by the pressure transducers P4 and P5 which are symmetric with respect to the longitudinal plane, their mean curves are reported in the third column of Fig. 6. Finally, in the second column, the pressure signals measured by the pressure transducer P2, which was located at the centre of the test article, are shown. The pressure peaks for each test and for each location are compared and reported in Fig. 7. With the exception of the DT3 test, where most likely the pressure signal were not acquired correctly, in each test the highest pressure was found at the centre of the bay (P1-P3). Comparing the tests on the two different configurations and carried out at the same nominal impact velocity, no significant differences were found.

Fig. 6. Pressure (filtered SAE180) vs. time

Fig. 7. Pressure peaks for each test
Test articles were irreversibly damaged during the drop tests DTR2, DT3, DT6 and DT7. As an example, the damaged test articles after the test DT3 (configuration 1) and the test (configuration 2), both performed at a nominal impact velocity of 8 m/s, are shown in Fig. 8 and Fig. 9, respectively. The damages (fiber failure, matrix cracking and delaminations) were found in four separate and symmetric zones (Z1, Z2, Z3 and Z4) which are indicated in Fig. 8 and Fig. 9. In order to evaluate the damage extension in each zone, a rectangle \((a \times b)\) was circumscribed about the damaged area in each zone. The dimensions of the rectangles are reported in Table 2. The test article TA4 with the skin layup configuration n. 2 was found more damaged than the TA2 manufactured with the configuration n.1. Moreover, it can be seen that the damage propagates along the direction of the external ply, that is along the 0° direction for the DT3 test and along the 45° direction for the DT7 test.

Non-destructive investigations are ongoing in order to better evaluate the internal damage extension and the damage shape caused by the water impact.
Table 2. Damaged area extension.

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Test Article</th>
<th>ZONE</th>
<th>a (mm)</th>
<th>b (mm)</th>
</tr>
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<tbody>
<tr>
<td>DT3</td>
<td>TA2</td>
<td>Z1</td>
<td>250</td>
<td>160</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Z2</td>
<td>320</td>
<td>280</td>
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<tr>
<td></td>
<td></td>
<td>Z3</td>
<td>385</td>
<td>135</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Z4</td>
<td>370</td>
<td>205</td>
</tr>
<tr>
<td>DT7</td>
<td>TA4</td>
<td>Z1</td>
<td>470</td>
<td>290</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Z2</td>
<td>355</td>
<td>350</td>
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<tr>
<td></td>
<td></td>
<td>Z3</td>
<td>400</td>
<td>235</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Z4</td>
<td>200</td>
<td>260</td>
</tr>
</tbody>
</table>

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References