

# Impact and quasi-static response of PVC/GRP marine sandwich laminates with and without cork inserts: Indenter effects

A.P. Abreu, L.S. Sutherland\*

*Centre for Marine Technology and Ocean Engineering (CENTEC), Instituto Superior Técnico, Universidade de Lisboa, Portugal.*

\*corresponding author l.sutherland@tecnico.ulisboa.pt

**ABSTRACT:** Composite material impact response is highly dependent on both impact event and materials parameters, but there are no standards tailored to those typical of the marine industry. As part of ongoing work to address this, the effects of impactor / indenter shape and size was investigated here via an extensive Quasi-static (QS) indentation and Low-velocity Impact (LVI) experimental study of a typical GRP/PVC marine sandwich laminate. Using equivalent QS & LVI tests enabled further exploration of the use of cheaper QS tests to evaluate LVI response. Further, comparisons with a novel marine GRP/PVC sandwich laminate with inserted cork layers were made. Complex and interacting response trends were seen, with clear differences across material configurations and impactor geometries. The Dynamic Scaling Factor (DSF), relating LVI and QS behaviour, was material-dependent but less influenced by impactor geometry. The findings successfully contribute to the development of future marine design guidelines and standardization efforts.

## 1 INTRODUCTION

The behaviour and resistance of composite laminated sandwich structures under out of plane low velocity impact (LVI) and quasi-static (QS) point loadings is a critical topic in marine structural design due to the potential for fragility and damage (Sutherland, 2018a). Further, the delamination aspects of the complex damage suffered is often hidden from view, and can lead to later damage progression and even catastrophic failure due to the often severe cyclic loadings inherent in the marine environment.

It is imperative that any testing is set up to emulate the specific impact scenario, since different impact events will lead to different impact behaviours, resistances and damage modes and progressions, and correspondingly both the impact response and the damage incurred is strongly dependant on the numerous material and test set-up parameters (Sutherland, 2018b; Sutherland and Guedes Soares, 2003). Hence, since the very nature of the relevant impact events in the marine environments (e.g. docking, floating objects etc.) differ wildly from those encountered in the aerospace industry (runway stones on take-off, hail, bird-strikes etc.) different LVI & QS test setups are required depending on the industry / end use. Similarly, the type of laminated composites used in the marine industry (typically lower fibre volume fraction, FVF, hand laid up or infused Glass Reinforced Plastics (polyester) - GRP) are very different from

those used in the aerospace industry (typically pre-impregnated high fibre volume fraction carbon epoxy). However, the available test standards have been developed by the aerospace industry and are tailored to the materials and impact scenarios of this industry - there are currently no standardized procedures specifically tailored to marine composite materials.

The present paper represents part of ongoing work to address this issue, by investigating a range of different LVI & QS scenarios (as many as feasible within the scope of this study) using a typical PVC-cored GRP sandwich marine laminate as a baseline for comparison. This paper extends previous research into a novel marine GRP-PVC sandwich laminate with inserted thin cork layers (Sutherland and Soares, 2022) by considering the effects of further test setup parameters.

The use of LVI and QS otherwise identical test setups continues previous research (Castilho et al., 2015; Sutherland et al., 2017; Sutherland and Guedes Soares, 2012; Sutherland and Soares, 2022) verifying the use of simpler, more accessible cheaper QS tests to obtain information on impact response and damage without the need of recourse to this more expensive and specialised impact testing, as well as addressing QS point loadings, which are themselves an important design consideration. Hence this study also extends ongoing assessments of when and where simpler quasi-static tests can predict impact behaviour, offering a more practical approach for safer, more efficient marine composites design.

## 2 EXPERIMENTAL PROCEDURE

This paper forms part of work extending the research completed in (Sutherland and Soares, 2022) which investigates the effects of using different test setups. Here, the impactor / indenter (the nomenclature for the same object impinging on the laminate for LVI and QS, respectively) parameter is varied, using a selection of impactor heads, or ‘tups’ (i.e. impactor / indenter) of various shapes and sizes.

### 2.1 Materials

Hence, the same materials as described in detail in (Sutherland and Soares, 2022) are considered here. A ‘baseline’ typical marine composite sandwich laminate was used as a reference to evaluate the performance of the laminates with cork layers against. This was a vacuum assisted hand layup GRP/PVC sandwich laminate with faces of Scott Bader Vinylester VE 679 PA (Pre-accelerated) resin reinforced with 3 plies of ‘ETL 800-1270’ Biaxial 0/90° 840 g/m<sup>2</sup> E-Glass together with a 20 mm thick ‘AIREX C70.75.20 P’ 80 kg/m<sup>3</sup> cross-linked PVC core.

The ‘cork-skinned’ concept is illustrated in its simplest form in Figure 1 (In this study, this thin cork layer is referred to as a ‘skin’ to distinguish from the outer GRP ‘faces’ of the sandwich laminates).

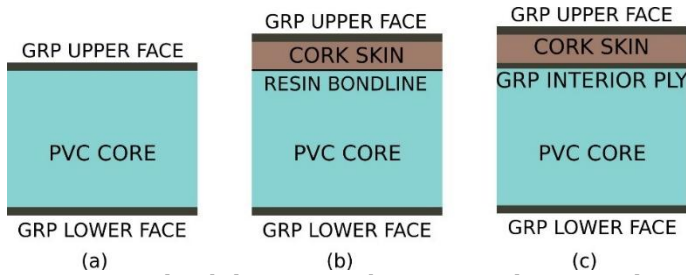


Figure 1: Sandwich laminate architectures and associated nomenclature (Sutherland and Soares, 2022)

Amorim Cork Composites Lda ‘Corecork’ NL20 (Amorim Cork Composites, 2017) was used, consisting of ground cork granules agglomerated with a proprietary binder. A range of cork-skinned sandwich laminate configurations (‘architectures’) was considered. The three parameters of this architecture thought most likely to influence the impact behaviour were studied in (Sutherland and Soares, 2022): (i) Cork skin thickness (2 or 4 mm), (ii) insertion of a single interior GRP ply between cork skin and PVC core, Fig. 1(c), and (iii) upper GRP face thickness (2 or 3 plies). The lower GRP face was of three plies in all laminates. All combinations of these parameters with at least 3 total upper and interior plies were studied, giving six candidate cork-skinned laminate architectures, seven with the ‘baseline’ simple PVC-cored laminate

Here, only the baseline and the two candidate cork-skinned laminates found to be most promising in (Sutherland and Soares, 2022) are considered: Laminate ‘1’ (baseline), laminate ‘4’ as that demonstrating

the best impact resistance for weight, and laminate ‘7’ as that exhibiting the best overall impact resistance irrespective of weight constraints. These architectures of these three laminates are shown in Table 1.

Table 1: Candidate sandwich laminates

| Laminate     | Core | Cork skin | Interior ply | Upper plies | Thickness [mm] |
|--------------|------|-----------|--------------|-------------|----------------|
| 1 (baseline) | PVC  | None      | None         | 3           | 24,8           |
| 4            | PVC  | 2 mm      | 1            | 3           | 26,8           |
| 7            | PVC  | 4 mm      | 1            | 3           | 29,6           |

### 2.2 Test setup

In order to extend the range of laminate architectures covered by the last author’s research evaluating the use of simpler Quasi-Static tests to obtain information about dynamic impact response normally investigated using low-velocity impact (LVI) testing (Castilho et al., 2015; Garrido et al., 2021; Sutherland and Soares, 2022), both types of tests were performed here. QS tests are not only much more accessible and economical, but the absence of vibrations which are super-imposed on LVI results damage events, and often partially or even totally obscure these damage events in LVI results, make their identification far easier from QS results.

To ensure valid comparisons between QS and LVI could be made, identical test setups (excluding the loading rate) in each equivalent case were used in both. QS indentation tests also serve to characterise and compare laminates for applications under static or very low loading rate point loads.

Using the same approach as detailed in (Sutherland and Soares, 2022), the ASTM standards D7136 and D6264 (ASTM, 2015, 2012) for ‘Drop-Weight Impact Events’ and ‘Concentrated Quasi-Static Indentation Force’ on fibre reinforced plastic composites, respectively, were used to design a ‘hybrid’ test setup applicable for both QS & LVI tests.

#### 2.2.1 Specimens and Support

Square specimens with dimensions of 75 mm × 75 mm were simply supported on a solid steel circular platform with a central opening of 50 mm diameter. A simply supported configuration was used to eliminate problems with the inconsistencies in clamping force and degree between quasi-static and dynamic tests inherent for a clamped setup.

#### 2.2.2 Impactors (‘Tups’)

The response of any material to an LVI or QS indentation event is completely dependent on the nature of that event, and one of the most important parameters in this sense is the shape and size of the impactor / indenter (Sutherland, 2018a, 2018b). Hence, to investigate the effects of this parameter 5 different sized and shaped impactors / indenters were used here;

Hemispherical-ended cylinders of 10 and 20 mm diameter (as those prescribed in the aerospace orientated standards to approximate hail and runway stones), Flat-ended cylinders of 10 and 20 mm diameter (to approximate blunter floating and dropped objects), and Pyramidal (to approximate sharper floating and dropped objects, such as fish boxes). All impactors / indenters were fabricated from stainless steel, and the dimensions of the Pyramidal are shown in Figure 2.

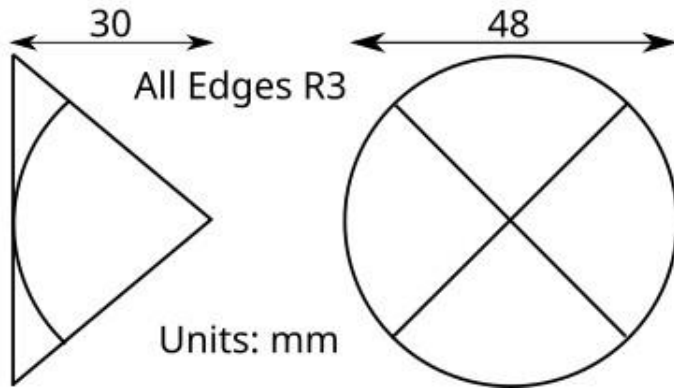


Figure 2: Pyramidal Impactor / Indenter

### 2.3 Test equipment and method

QS tests were performed on a calibrated servo-hydraulic machine under displacement control at a constant indentation velocity of 0.5 mm/s. As the most important in-service damage level in a marine environment, the perforation of the upper sandwich face was used as the critical damage event here. However, to ensure that this perforation was entirely captured, and to provide extra data for analyses in later studies, QS tests were continued until the perforation of the lower face.

Impact tests were performed on a Rosand IFW5 instrumented drop weight machine. Since an unlimited number of specimens was not available, estimation of the Incident Kinetic Energy (IKE) require for perforation in each case was estimated using a 'Dynamic Scaling Factor (DSF)' developed in previous work (Castilho et al., 2015; Garrido et al., 2021; Sutherland and Soares, 2022). The DSF is simply the ratio of the energy required to reach a given damage event in an LVI test to that required in a QS test.

This previous research has shown that for typical marine sandwich laminates this DSF is typically approximately 1.5, and up to 2. Since LVI tests are impossible to stop mid test, unlike QS tests, the target LVI IKE was set in each case to give upper face perforation but not total sandwich perforation to avoid potential damage to the sensitive equipment instrumentation, by using the values obtained from QS tests together with an estimated DSF of 1.5, as a typical value. The actual DSF values were then calculated once LVI results were obtained, and will be presented later.

For both QS & LVI, at least 3, and 5 where sufficient material was available, repetitions of each test was made. The overall test programme structure is most concisely explained by simply providing the specimen identification coding system (which will also aid interpretation of some of the figures presented in the following section):

### Specimen Codes

QS - Laminate - Indenter - Repetition

I - Laminate - Indenter - Repetition

QS / I = QS or LVI test

Laminate = 1, 4 or 7

Indenter / Impactor:

F10: Flat, Ø 10 mm

F20: Flat, Ø 10 mm

H10: Hemispherical Ø 10 mm

H20: Hemispherical Ø 10 mm

P: Pyramidal

Repetition: 3, or 5 where specimens available.

e.g. QS-1-P-2 = Quasi-Static test of Laminate 1 (base-line PVC sandwich) indented with Pyramidal indenter, second repetition.

## 3 RESULTS AND DISCUSSION

### 3.1 Failure Modes

As stated above, the failure mode considered in this paper is that of perforation of the upper GRP face. However, the following test setups did not produce this failure mode due to higher loadings in comparison with the specimen area leading to premature crushing of the foam core, before perforation of the upper face.

QS & I - 1, 4 & 7 - F20

QS & I - 7 - H20

As an invalid failure mode for this paper, the results of these specimens with core crushing were hence not considered further. This provides valuable information for the overall aim of the research, of which this paper is only part, of developing test standards for marine composite laminates, indicating which test setups are not suitable. The use of a larger, 20 mm flat-ended tup is to be avoided for this size of specimen, and a larger 20 mm hemispherical-ended tup may give problems for laminates with thicker, stiffer and more perforation resistant upper faces.

Composite materials display complex, multiple and interacting failure modes under point loadings due to their heterogeneous and anisotropic nature. Common failure modes include matrix cracking, fibre breakage, delamination, and fibre-matrix de-bond-

ing, which can occur independently or simultaneously, significantly impacting structural integrity. The complex failure modes seen here are fully illustrated and discussed in detail in (Abreu, 2025), here they are addressed in terms of specific damage events.

‘Perforation’ of the upper face, the critical damage event of this paper, requires far more care in its definition than is immediately apparent. To enable fair comparisons to be made, a both relevant and consistent definition for ‘perforation’ and when it is deemed to have occurred must be made. This is complicated here by the use of different shaped and sized tups. To aid the rationale of this definition The Force and Absorbed Energy (AE) - Displacement behaviours seen for the various tups are show in Figure 3 & Figure 4, respectively (laminates 1 is shown as an example in both cases since very similar behaviour trends were seen for all three laminates).

Perforation, as observed visually in the QS tests, is seen to correspond to a drop in Force (and associated inflection in AE). However, this speed of this Force varies with tup, the pyramidal tup producing a far more gradual drop than the smallest hemispherical one, for example (which is a direct result of the more gradual, increasing damage area with the former compared to the sudden punch through, classic ‘perforation’ of the latter). However, except for the pyramid, the force then drops to a lower ‘plateau’ which can be identified as when the indenter / impactor has passed completely through the upper face, ‘perforation’ has occurred. To ensure that this plateau had been reached, ‘perforation’ was hence defined as having been completed at a displacement of 16 mm as indicated by the dashed lines in Figure 3 and Figure 4.

Although such a clear plateau is not seen for the pyramid, since damage continues to grow due to its geometry, it is seen that by 16 mm of displacement there is a significant drop in Force and hence this definition is also physically relevant to these tests, and, most importantly, enables a fair comparison of ‘perforation’ with the other tup geometries.

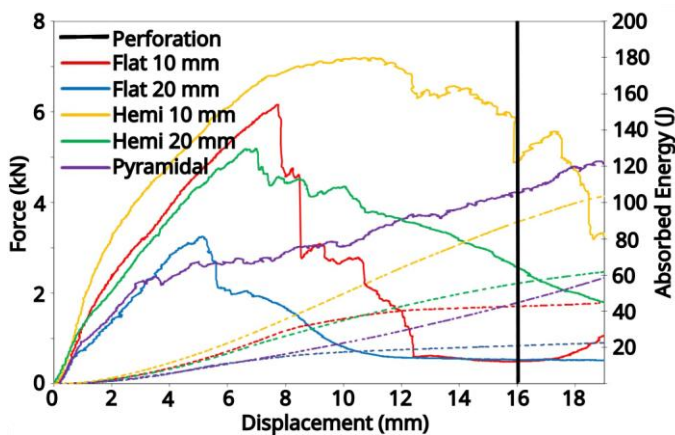


Figure 3: Typical (Laminate 1, GRP-PVC baseline) illustrative effects of indenter shape and size on QS Force (solid lines) and Absorbed Energy (dotted lines) vs Displacement

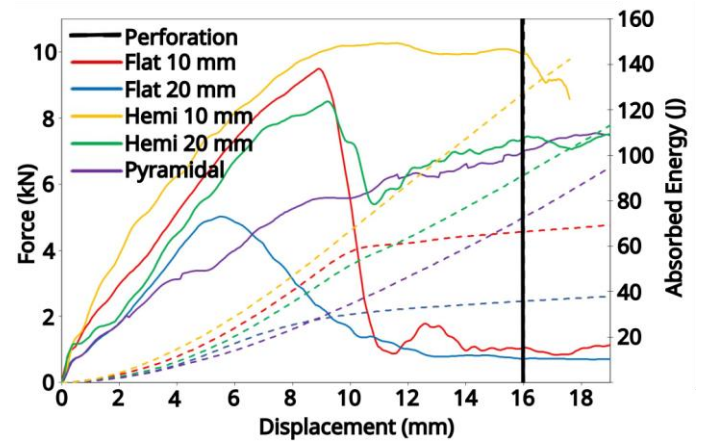


Figure 4: Typical (Laminate 1, GRP-PVC baseline) illustrative effects of impactor shape and size on LVI Force (solid lines) and Absorbed Energy (dotted lines) vs Displacement

In terms of results, there are three main practically relevant responses that may be retrieved from the data and compared: Maximum Force, AE at Maximum Force and AE at Perforation. The first two responses are relevant when the impact behaviour required is a reduction in reaction forces (‘Protection’) and the latter when ‘Resistance’ is required. These two requirements are usually mutually opposed – lower forces are generally attained via damage, which reduces perforation resistance. Maximum force occurs as the perforation process is commenced, with fibre fracture well underway, perforation has been discussed above.

### 3.2 Maximum Force

For such a multi-parameter (sandwich laminate architecture and impactor / indenter shape and form) factorial study, the use of interaction plots presents most clearly not only the parameter effects but interactions between these effects (in fact they are necessary to show these interactions) (Sutherland et al., 1999). Hence, the full set of results for both maximum force and AE to this maximum force for both QS & LVI are presented as interaction plots Figure 5 to Figure 8.

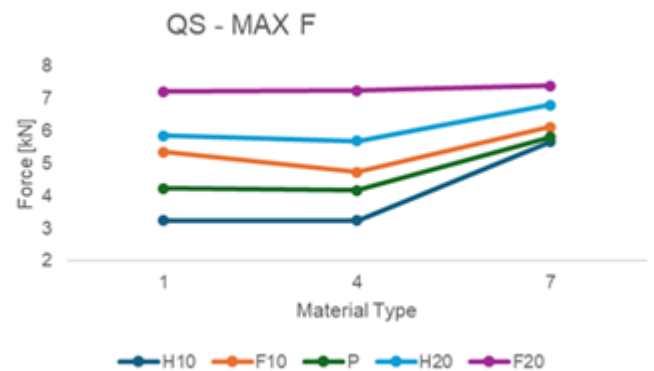


Figure 5: QS maximum force

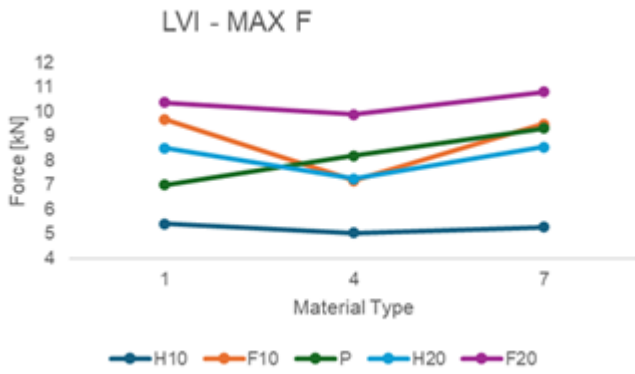


Figure 6: LVI maximum force

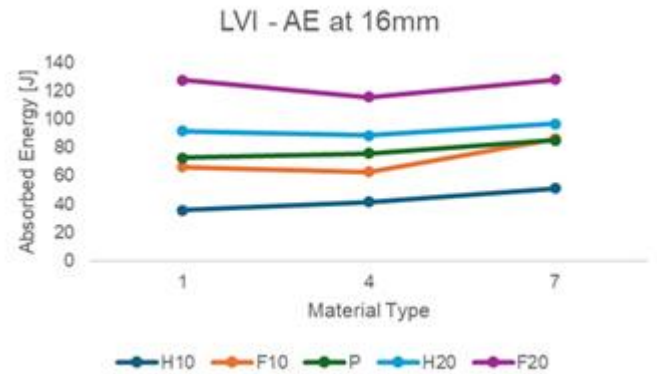


Figure 10: Absorbed energy at defined perforation for LVI

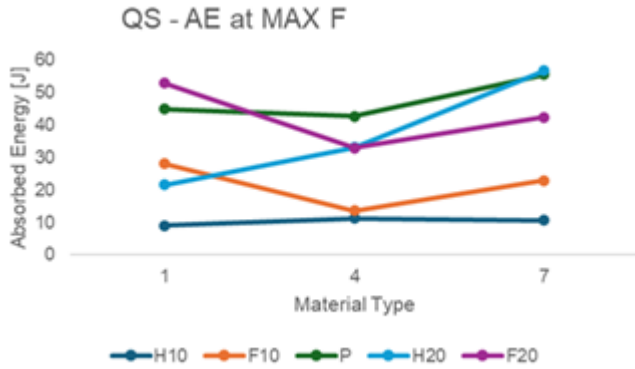


Figure 7: QS AE at maximum force

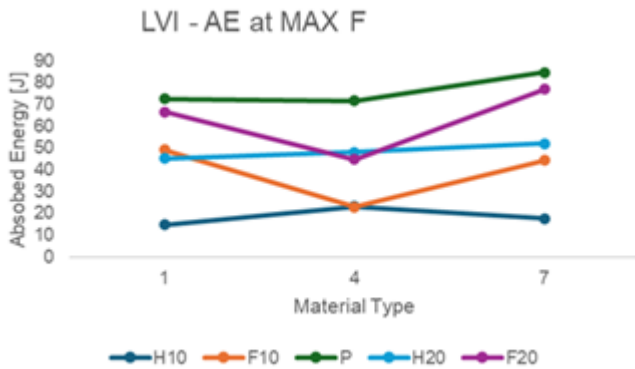


Figure 8: LVI AE at maximum force

### 3.3 Perforation

Similarly, the full set of AE to perforation results for both QS & LVI are presented as interaction plots Figure 9 and Figure 10.

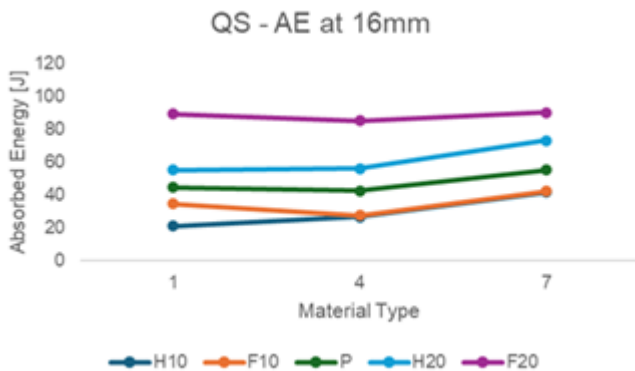


Figure 9: Absorbed energy at the defined perforation for QS

### 3.4 Dynamic Scaling Factor (DSF)

The DSF (ratio of the LVI to the QS results) values for maximum force, AE to maximum force and AE to perforation (defined as at 16 mm displacement) are presented first in terms of laminate and then in terms of tup in Figure 11 and Figure 12, respectively.

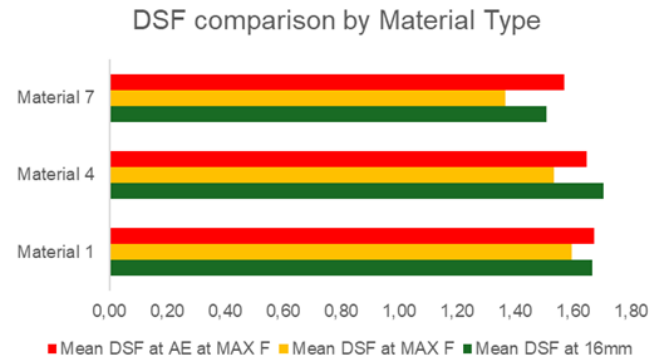


Figure 11: DSF by laminate

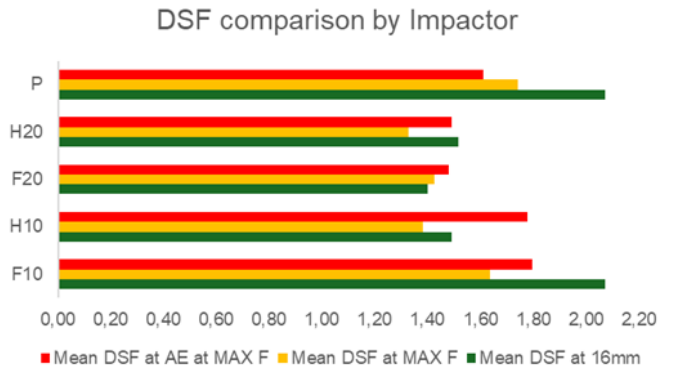


Figure 12: DSF by tup size and shape

## 4 DISCUSSION

Detailed identifications and deductions of the very complex trends and behaviours seen in the results plots of the previous section have been lengthily discussed with respect to failure modes and observed events, and with recourse to the other alternative, equivalent interaction plots of the data (separate plots for each laminate of QS and LVI vs tup, plus separate plots for each tup of QS and LVI vs laminate) in (Abreu, 2025). Here there is no space, nor need, to

replicate this and the already very complex and extensive main trends are summarised below. Engineering interpretations of the practical implications of these trends are then detailed.

#### 4.1 Parameter effects

##### Variation between laminates

- For all three materials (1, 4, and 7), AE was consistently higher under LVI conditions than QS conditions.
- Material 1 and Material 4 exhibited very similar DSF values, with overall DSFs close to the 1.6 value reported by Sutherland for thick laminates.
- Material 7 consistently showed lower DSF values across all energy criteria, suggesting a deviation from the scaling rule applicable to Materials 1 and 4.
- AE and force trends in Material 7 were generally smoother and more consistent than in the other two, with less variation across impactors.
- At maximum force before perforation, the AE values and peak forces for Material 7 were lower under LVI than for Materials 1 and 4.

##### Effect of tup size and shape

- Across all materials and metrics, the F20 and H20 impactors recorded the highest AE values, both in QS and LVI.
- The pyramidal impactor presented relatively linear increases in AE and force across materials, maintaining intermediate DSF values ( $\sim 1.8$ ), which is consistent with Sutherland's expectations.
- The F10 impactor showed the highest DSF ( $\sim 2.08$  at 16 mm), suggesting significant differences in energy absorption depending on test type.
- Impactors like F10 and P exhibited sharper contrasts in AE and force between QS and LVI conditions, compared to hemispherical ones.
- Flat impactors produced the highest AE at perforation (especially F20), due to the larger contact area causing widespread crushing.
- Hemispherical impactors, particularly H10, showed lower AE values but with smoother force-displacement behaviour.
- Pyramidal impactors led to localized, sharp force increases and moderately high AE, reflecting concentrated stress paths.
- The DSF varied significantly with shape: Flat impactors showed high DSFs, pyramidal moderate, and hemispherical lower.

##### QS vs. LVI (effect of loading rate)

- AE at 16 mm for LVI tests was consistently higher than in QS, across all materials and impactor types.
- Maximum force before perforation was higher in LVI than QS in nearly all conditions, with few exceptions (e.g., QS-7-H10).
- QS tests demonstrated more progressive load increase with fewer oscillations, while LVI curves showed clearer force peaks followed by sudden drops.
- AE at maximum force before 16 mm also followed the trend: LVI generally exceeded QS.
- The difference in AE and force between QS and LVI is attributed primarily to loading rate sensitivity of the materials.
- Materials 1 and 4, being more sensitive, displayed DSFs near 1.6, supporting the scaling assumptions from Sutherland's work.
- Material 7 showed lower loading rate sensitivity, with DSFs around 1.48, suggesting it may be less influenced by loading rate or possibly because of the cushioning effect of the thick cork.

##### Parameter interaction effects

- In most plots, the AE increase in LVI vs. QS was nearly linear, especially for F20 and H20, indicating predictable strain-rate effects.
- Cross plots by material revealed that trends across impactor types are generally preserved in both QS and LVI, confirming the dominance of geometry in driving failure mode and energy absorption.
- Cross plots by impactor showed material-based trends more clearly, emphasizing how different core types influence total AE and peak forces.

#### 4.2 Engineering interpretations of parameter trends

##### Variation between laminates

- Materials 1 and 4 showed behaviour aligned with literature on thick laminates with thermoset matrixes, including strong agreement with Sutherland's DSF of 1.6.
- Material 7 deviated from this expected behaviour, particularly in its lower DSF and milder AE and force curves. This may be indicative of a different dominant failure mechanism or enhanced damping.
- Material 7's more gradual AE increase and lower peak forces may imply better damage diffusion, possibly linked to fibre orientation, core compressibility, or resin brittleness.

## Effect of tup size and shape

- The larger flat and hemispherical impactors (F20 and H20) tend to cause more extensive damage, leading to higher AE values and higher DSFs.
- Flat impactors introduce more distributed compression, possibly encouraging more matrix-dominated failures and core crushing. This contributes to the elevated DSFs.
- Pyramidal impactors, with their sharp profile, may initiate fibre and matrix damage earlier, without allowing enough delamination or crushing, leading to intermediate AE and DSF values.
- Impactor geometry plays a pivotal role in determining both failure mode and test metrics like AE and peak force.
- As the contact area increases (e.g., from P to H20 to F20), the likelihood of initiating extensive delamination and core crushing rises. This is evidenced by DSF values that scale similarly with impactor type and contact area.

## QS vs. LVI (effect of loading rate)

- The differences between QS and LVI, especially in AE and maximum force, support the known phenomenon of strain-rate dependence in composite failure.
- LVI promotes more brittle failure and fibre breakage, leading to sudden load drops and higher energy absorption at specific points (e.g., maximum force or 16 mm displacement).
- QS tests, on the other hand, allow more time for delamination and matrix cracking to propagate, often resulting in smoother but lower energy absorption curves.
- DSF is a practical tool for understanding how loading rate influences composite energy absorption.
- While the Sutherland value of 1.6 holds for Materials 1 and 4, Material 7's lower DSF suggests reduced sensitivity to loading rate, perhaps due to improved fibre-matrix compatibility or enhanced structural damping.
- Impact-driven damage tends to localize more, while QS loading allows more interaction among layers and gradual failure. This difference may explain lower AE in QS across all impactors and materials.

## Parameter interaction effects

- The different ways of plotting the data (by material, impactor, and test type) highlight complex interdependencies.
- For example, the AE at 16 mm grows with impactor size and flatness in both QS and LVI, but

with different slopes, reflecting the additional influence of rate effects.

- DSF trends observed through cross plots affirm the need to evaluate scaling by material rather than geometry alone, as some geometries yield inconsistent DSFs across different materials.

## 5 CONCLUSIONS

An extensive experimental study has been performed on the Quasi-static indentation (QS) and Low-velocity Impact responses of two versions of a novel marine GRP-PVC sandwich laminate with inserted thin cork layers, extending the scope of previous research (Sutherland and Soares, 2022) by considering the effects of further test setup parameters, namely indenter / impactor 'tup' size (10 and 20 mm diameter) and shape (flat, hemispherical and pyramidal) on a 50 mm circular support. A typical GRP/PVC 'baseline' laminate was used as a comparison.

The trends seen were complex and have been described by interaction 'cross' plots to show how trends in one parameter often change depending on the value of other parameter(s), and then trends have been summarised and also described in terms of an 'engineering interpretation'.

Key mechanical responses maximum force, absorbed energy at this maximum force and absorbed energy after upper face perforation were extracted. The results show clear differences in mechanical response across material configurations and impactor geometries. Notably, the Dynamic Scaling Factor (DSF), which relates LVI and QS behaviour, proved to be material-dependent and less influenced by impactor geometry. The findings offer valuable insights into failure mechanisms, energy absorption characteristics, and the comparative behaviour of static and dynamic loading in composite sandwich panels, contributing to the development of future design guidelines and standardization efforts.

## 6 ACKNOWLEDGEMENTS

This work contributes to the CENTEC Strategic Research Plan under FCT contract UID-00134-2025.

## 7 REFERENCES

- Abreu, A.P., 2025. Impact on cork-skinned marine PVC/GRP sandwich laminates (MSc). Instituto Superior Técnico, Lisboa.
- Amorim Cork Composites, 2017. Corecork NL20 Material Datasheet (Datasheet No. ACC.764). Amorim Cork Composites.

- ASTM, 2015. ASTM D7136-15 Standard Test Method for Measuring the Damage Resistance of a Fiber-Reinforced Polymer Matrix Composite to a Drop-Weight Impact Event (Standard). ASTM International.
- ASTM, 2012. ASTM D6264-12 Standard Test Method for Measuring the Damage Resistance of a Fiber-Reinforced Polymer-Matrix Composite to a Concentrated Quasi-Static Indentation Force (Standard). ASTM International.
- Castilho, T., Sutherland, L.S. & Guedes Soares, C., 2015. Impact resistance of marine sandwich composites, in: *Maritime Technology and Engineering - Proceedings of MARTECH 2014: 2nd International Conference on Maritime Technology and Engineering*. Taylor & Francis Group, London, UK, pp. 607–618.
- Garrido, M., Teixeira, R., Correia, J. & Sutherland, L.S., 2021. Quasi-static indentation and impact in glass-fibre reinforced polymer sandwich panels for civil and ocean engineering applications. *J. Sandw. Struct. Mater.* 109963621983013.
- Sutherland, L.S., 2018a. A review of impact testing on marine composite materials: Part I – Marine impacts on marine composites. *Compos. Struct.* 188: 197–208.
- Sutherland, L.S., 2018b. A review of impact testing on marine composite materials: Part II – Impact event and material parameters. *Compos. Struct.* 188: 503–511.
- Sutherland, L.S. & Guedes Soares, C., 2012. The use of quasi-static testing to obtain the low-velocity impact damage resistance of marine GRP laminates. *Compos. Part B Eng.* 43: 1459–1467.
- Sutherland, L.S. & Guedes Soares, C., 2003. The effects of test parameters on the impact response of glass reinforced plastic using an experimental design approach. *Compos. Sci. Technol.* 63: 1–18.
- Sutherland, L.S., Sá, M.F., Correia, J.R., Guedes Soares, C., Gomes, A. & Silvestre, N., 2017. Impact response of pedestrian bridge multicellular pultruded GFRP deck panels. *Compos. Struct.* 171: 473–485.
- Sutherland, L.S., Shenoi, R.A. & Lewis, S.M., 1999. Size and scale effects in composites: II. Unidirectional laminates. *Compos. Sci. Technol.* 59: 221–233.
- Sutherland, L.S. & Soares, C.G., 2022. Impact resistance of cork-skinned marine PVC / GRP sandwich laminates. *Thin-Walled Struct.* 180: 109830.