

# Influence of the Metal Volume Fraction on the permanent dent depth and energy absorption of GLARE plates subjected to low velocity impact

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**Abstract.** Fiber-metal laminates are hybrid composite materials, consisting of alternating metal layers bonded to fiber-reinforced prepreg layers. GLARE (GLAss REinforced) belongs to this new family of materials. GLARE is the most successful fiber-metal laminate up to now and is currently being used for the construction of primary aerospace structures, such as the fuselage of the Airbus A380 air plane. Impact properties are very important in aerospace structures, since impact damage is caused by various sources, such as maintenance damage from dropped tools, collision between service cars or cargo and the structure, bird strikes and hail. The principal objective of this article is to evaluate the influence of the Metal Volume Fraction (MVF) on the low velocity impact response of GLARE fiber-metal laminates. Previously published differential equations of motion are employed for this purpose. The low velocity impact behavior of various circular GLARE plates is predicted and characteristic values of impact variables, which represent the impact phenomenon, are evaluated versus the corresponding MVF of the examined GLARE material grades. The considered GLARE plates are subjected to low velocity impact under identical impact conditions. A strong effect of the MVF on the permanent dent depth and energy absorption of GLARE plates has been found.

## 1. Introduction

Fiber-metal laminates are hybrid composite materials, consisting of alternating metal layers bonded to fiber-reinforced prepreg layers. ARALL (Aramid Reinforced ALuminum Laminates), CARALL (Carbon Reinforced ALuminum Laminates) and GLARE (GLAss REinforced) belong to this new family of materials. GLARE is the most successful fiber-metal laminate up to now and is currently being used for the construction of primary aerospace structures, such as the fuselage of the Airbus A380 air plane. Further applications have also been considered: aircraft cargo floors of Boeing 777, aircraft engine cowlings, bonded GLARE patch repair, aircraft stiffeners with a wide variety of shapes, cargo containers, seamless GLARE tubes.

Impact properties are very important in aerospace structures, since impact damage is caused by various sources, such as maintenance damage from dropped tools, collision between service cars or cargo and the structure, bird strikes and hail [1]. Much work has been published on the subject of impact, concerning conventional composite materials, which are frequently used in aerospace structures. Analytical, numerical and experimental impact studies have been considered. Recently, due to the importance of understanding the response of GLARE structures to impact loading, many



researchers have studied impact phenomena concerning GLARE. In these studies, the low and high velocity impact, and the ballistic impact response of GLARE are analyzed.

This article focuses on predicting the influence of Metal Volume Fraction (MVF) on the response of thin circular clamped GLARE plates, subjected to low velocity impact. Low velocity impacts represent damage from service trucks, cargo containers and dropped tools during maintenance [1]. A typical test method, employed by researchers in order to study the low velocity impact behavior of GLARE, is to apply impact loads on circular clamped plates using a drop weight impact tester, equipped with a hemispherical impactor [1, 2]. Consequently, prediction of the response of circular GLARE plates to low velocity impact has great practical importance.

This article deals with the theoretical prediction of the dynamic response of thin circular clamped GLARE plates, subjected to low velocity impact by a lateral hemispherical impactor, striking at their center. In the work of Guocai et al. this problem was studied experimentally [2]. Caprino et al. [3, 4] developed a mechanistic model to predict the response of square fibreglass-aluminum laminates under low velocity impact, which requires the implementation of several experimental tests. Hoo Fatt et al. [5] employed a spring-mass model to predict the ballistic response of clamped square GLARE panels. In two articles by Tsamasphyros and Bikakis, the differential equations of motion, corresponding to the impact of a hemispherical impactor striking on a circular clamped GLARE plate, were derived using a spring-mass model as well [6] and solved [7].

The principal objective of this article is to evaluate and compare the influence of the MVF on the permanent dent depth and impact energy absorption of thin circular clamped fiber-metal laminates consisting of different standard GLARE grades. Previously published equations are employed for this purpose. The low velocity impact behavior of GLARE 2A-3/2-0.4, GLARE 2A-4/3-0.238, GLARE 3-3/2-0.4, GLARE 4-3/2-0.317, GLARE 5-3/2-0.233, GLARE 2A-4/3-0.256, GLARE 4-3/2-0.342 and GLARE 5-3/2-0.283 circular plates of equal total thickness and of equal areal weight, for various diameters, is predicted under identical impact conditions. Then, the effect of the MVF of these GLARE grades on the permanent dent depth and impact energy absorption is compared and analyzed, in connection with the thickness and the areal weight of the plates. The presented results shed light to the impact response of GLARE fiber-metal laminates and will help engineers and researchers to understand the behavior of the examined GLARE grades. The derived conclusions can be used for the design of GLARE structures when their exposure to low velocity impact is expected. To the authors' knowledge, no other similar impact study concerning GLARE fiber metal laminates has been published in the current scientific literature.

## 2. Analytical equations

We consider a thin clamped circular GLARE plate with radius  $\alpha$  and thickness  $h$ . The plate is struck at its center by an impactor with large mass  $M_0$  and initial kinetic energy  $E_k$ . The impactor has a hemispherical tip with radius  $R$ . The plate consists of alternating layers of aluminum and glass-epoxy. The aspect ratio  $\alpha/h$  is assumed high, so that shear deformation and local indentation are negligible. The plate is clamped along its boundary. As the impactor progresses, the load  $P$  due to the global deflection of the plate and the corresponding central plate deflection  $w_o$  increase, while the velocity of the impactor decreases, until the plate reaches its maximum deformation. At this point, due to the elastic strain energy of the prepreg layers, which have been stretched during the loading stage, the plate starts to move toward the opposite direction, until the impact load  $P$  becomes equal to zero. Using a spring-mass model, the differential equations of motion corresponding to this physical phenomenon were derived in reference [6] and solved in reference [7]. Here, the basic employed equations from reference [7] for our calculations are presented. These equations have been validated by comparisons with experimental data [6, 7]. For large plate deflections, the impact load during loading is given by:

$$P_L(w_o) = K_p w_o + K_{el} w_o^3 \quad (1)$$

Equation (1) is valid for  $0 \leq w_o \leq w_o^{\max}$  where  $w_o^{\max}$  is the maximum central plate deflection due to the impact. The corresponding unloading impact load is given by:

$$P_U(w_o) = K_p(2w_o - w_o^{\max}) + K_{el}w_o^3 \quad (2)$$

Equation (2) is valid for  $w_o^f \leq w_o \leq w_o^{\max}$ , where  $w_o^f$  is the final deflection of zero impact load. It is noted that the final deflection is equal to the permanent dent depth caused by the impact on the GLARE plate [6]. Analytical expressions to calculate  $w_o^{\max}$  and  $w_o^f$  can be found in reference [7].

The coefficients  $K_p$  and  $K_{el}$  are as follows [6-8]:

$$K_p = 0.576N_x + 0.576N_y + 0.734N_{xy} \quad (3)$$

$$K_{el} = [0.62A_{11} + 0.62A_{22} + 0.412(A_{12} + 2A_{66})] \frac{1}{\alpha^2} \quad (4)$$

The in-plane forces  $N_x$ ,  $N_y$  and  $N_{xy}$  of the aluminum layers are [6-8]:

$$N_x = N_y = m\sigma_o t_{Al}, \quad N_{xy} = m \frac{\sigma_o}{\sqrt{3}} t_{Al} \quad (5)$$

where  $m$  is the number of aluminum layers,  $\sigma_o$  is the yield stress of aluminum and  $t_{AL}$  is the thickness of each aluminum layer.  $A_{ij}$  are the extensional stiffnesses of the laminate.

The low velocity impact is simulated in three stages. During the first stage, the impactor starts to deform the plate until internal damage due to delamination occurs. For the first impact stage, the time interval  $\Delta t_1$ , in order for the impactor to move from the initial position  $w_o^1 = 0$  to an arbitrary position  $w_o^2 \leq w_o^d$ , is calculated numerically by the following integration:

$$\Delta t_1 = \int_0^{w_o^2} \frac{dw_o}{\sqrt{v^2 - \frac{K_p w_o^2}{M_o + m_e} - \frac{K_{el} w_o^4}{2(M_o + m_e)}}} \quad (6)$$

where  $w_o^d$  is the delamination position calculated using the pertinent analytical equation of reference [7]. The initial velocity  $v$  of the impactor is equal to  $\sqrt{2E_k / M_o}$  and  $m_e$  is the effective plate mass calculated as indicated in [6, 7, 9].

The corresponding kinetic energy is:

$$E_k = \frac{1}{2} M_o \left( v^2 - \frac{K_p w_o^2}{M_o + m_e} - \frac{K_{el} w_o^4}{2(M_o + m_e)} \right) \quad (7)$$

The second impact stage starts after delamination and continues up to the position of maximum plate deformation  $w_o^{\max}$ . For the second impact stage, the time interval  $\Delta t_2$ , in order for the impactor to move from the initial position  $w_o^1 = w_o^d$  to an arbitrary position  $w_o^2 \leq w_o^{\max}$ , is calculated numerically by the following integration:

$$\Delta t_2 = \int_{w_o^d}^{w_o^2} \frac{dw_o}{\sqrt{v^2 - \frac{2E_{del}}{M_o + m_e} - \frac{K_P w_o^2}{M_o + m_e} - \frac{K_{el} w_o^4}{2(M_o + m_e)}}} \quad (8)$$

$E_{del}$  is the energy required for the sudden delamination among glass-epoxy layers, and can be calculated as indicated in references [5-7, 9-12].

The kinetic energy during the second stage is given by:

$$E_k = \frac{1}{2} M_o \left( v^2 - \frac{2E_{del}}{M_o + m_e} - \frac{K_P w_o^2}{M_o + m_e} - \frac{K_{el} w_o^4}{2(M_o + m_e)} \right) \quad (9)$$

The third impact stage starts from the position of maximum plate deformation  $w_o^{\max}$  and is completed when the impact load becomes equal to zero. For this impact stage, the time interval  $\Delta t_3$ , in order for the impactor to move from the initial position  $w_o^1 = w_o^{\max}$  to an arbitrary position  $w_o^2 \geq w_o^f$ , is calculated numerically by the following integration:

$$\Delta t_3 = \int_{w_o^{\max}}^{w_o^2} \frac{-dw_o}{\sqrt{\frac{2K_P w_o (w_o^{\max} - w_o) + 0.5K_{el} (w_o^{\max 4} - w_o^4)}{M_o + m_e}}} \quad (10)$$

The kinetic energy during the third stage is given by:

$$E_k = \frac{1}{2} M_o \left( \frac{2K_P w_o (w_o^{\max} - w_o) + 0.5K_{el} (w_o^{\max 4} - w_o^4)}{M_o + m_e} \right) \quad (11)$$

### 3. Results

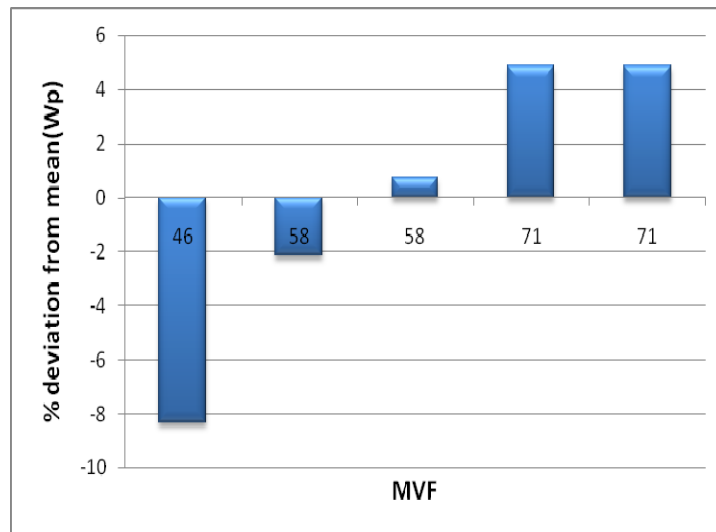
We consider plates with identical total thickness equal to 1.7 mm consisting of the following standard grades: GLARE 2A-3/2-0.4, GLARE 2A-4/3-0.238, GLARE 3-3/2-0.4, GLARE 4-3/2-0.317 and GLARE 5-3/2-0.233. We also consider plates with identical areal weight equal to  $4.23 \times 10^{-5}$  N/mm<sup>2</sup> consisting of the following standard grades: GLARE 2A-3/2-0.4, GLARE 2A-4/3-0.256, GLARE 3-3/2-0.4, GLARE 4-3/2-0.342 and GLARE 5-3/2-0.283.

The examined GLARE plates consist of alternating S2-glass UD fiber prepreg layers and 2024-T3 aluminum layers. Each prepreg ply has a thickness of 0.125 mm. All aluminum layers of each GLARE plate have equal thickness. We apply the equations presented in the previous section in order to calculate the low velocity impact response of the aforementioned standard GLARE grades. The material properties considered for our calculations are from references [1, 5, 13]. The prepreg tensile failure strain, aluminum and prepreg weight density, have been determined from our correspondence with the manufacturer of GLARE. We have analyzed circular plates with 50 mm, 65 mm and 80 mm radiuses for each of the considered different GLARE configurations.

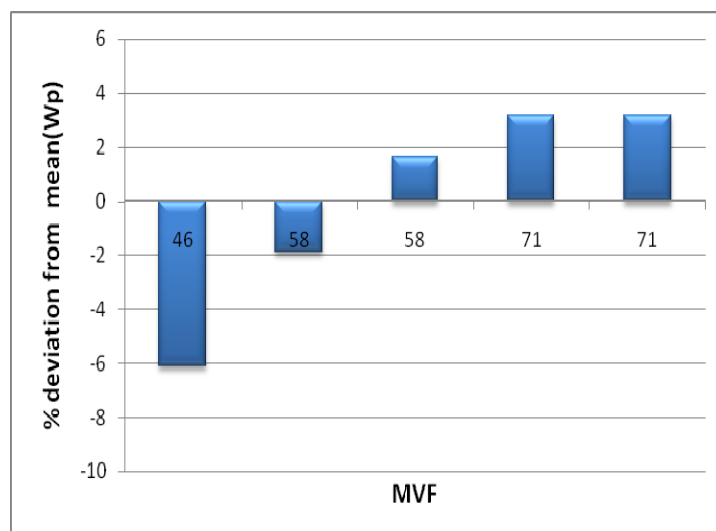
We consider that the impactor has a mass of 6.29 Kg, which is the same as in the experiments of [2], and initial kinetic energy equal to 13 J in all examined impact cases. At this energy level, the

velocity of the impactor is low yielding no sensitivity of the material properties related to strain rates effects [4, 14]. Furthermore, we have calculated using the analytical model of reference [8] the first failure energy of all examined GLARE plates under static lateral indentation and verified that it is greater than 13 J in all cases. As explained in reference [6], this verification yields that the considered initial kinetic energy of the impactor does not cause first failure of the glass-epoxy layers due to tensile fracture.

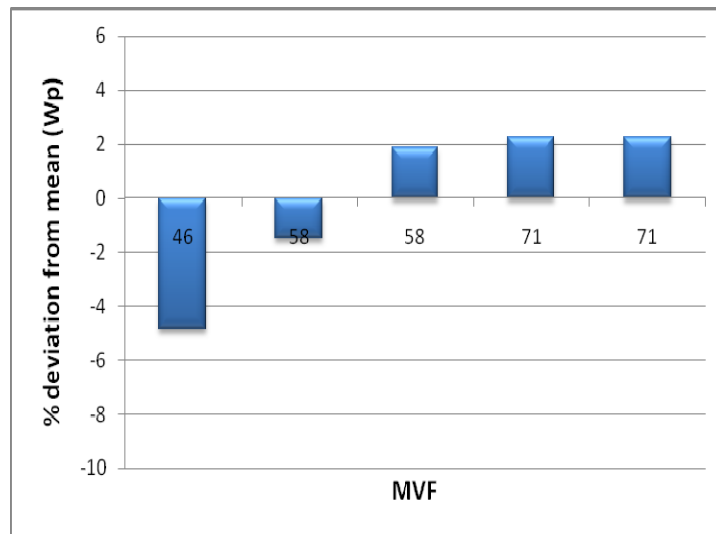
In figures 1-3 the % deviation from the average permanent dent depth due to impact versus the MVF, of GLARE plates with 50 mm, 65 mm and 80 mm radius is depicted. The plates have equal areal weight. MVF is defined as the ratio of the total thickness of aluminum layers divided by the laminate thickness, and is expressed as % percentage. A strong effect of the MVF on the permanent dent depth can be observed in these figures. It can also be observed that for increasing MVF, the permanent dent depth increases. This trend is also valid for GLARE plates with equal thickness, with the exception of GLARE 2A-4/3-0.238, which has MVF equal to 56.



**Figure 1.** Permanent dent depth vs MVF of plates with equal areal weight and 50 mm radius



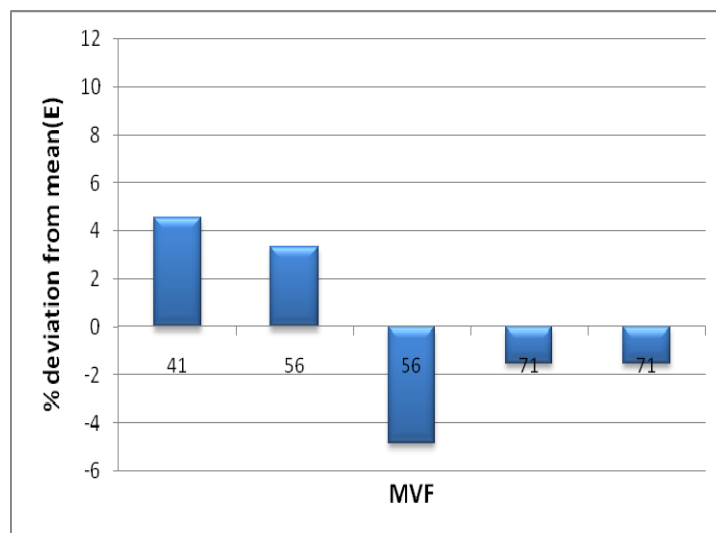
**Figure 2.** Permanent dent depth vs MVF of plates with equal areal weight and 65 mm radius



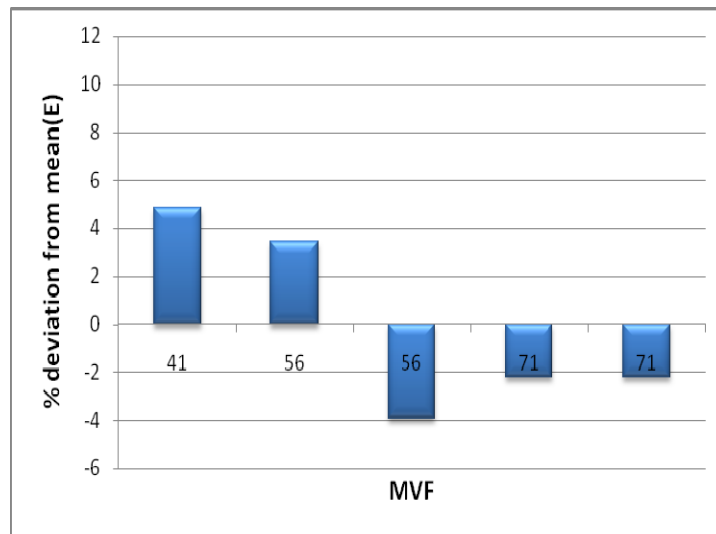
**Figure 3.** Permanent dent depth vs MVF of plates with equal areal weight and 80 mm radius

In figures 4-6 the % deviation from the average permanently absorbed impact energy versus the MVF, of GLARE plates with 50 mm, 65 mm and 80 mm radius is depicted. The plates have equal thickness. A strong effect of the MVF on the permanently absorbed impact energy can be observed in these figures. It can also be observed that for increasing MVF, the permanently absorbed impact energy decreases, with the exception of GLARE 2A-4/3-0.238, which has MVF equal to 56.

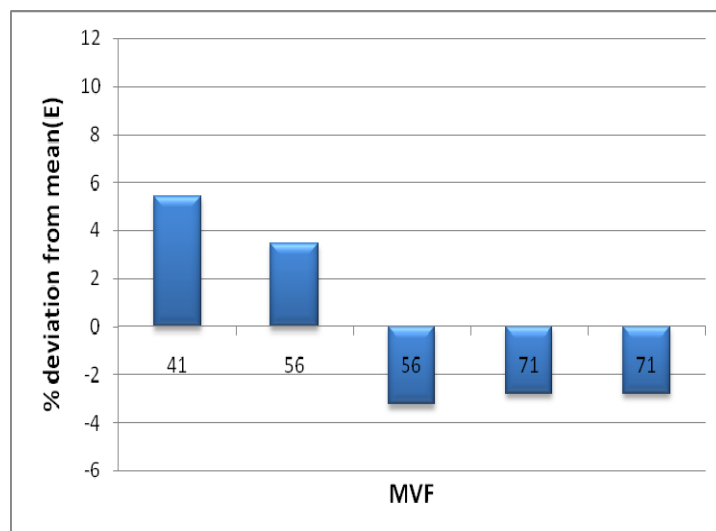
Based on our results, it is found that MVF can be used as a qualitative design parameter in order to alter the permanent dent depth and the absorbed impact energy of GLARE plates with equal thickness or equal areal weight in a consistent manner, provided that the basic lay-up, number of aluminum and prepreg layers, does not change, as it changes in the case of GLARE 2A-4/3.



**Figure 4.** Absorbed energy vs MVF of plates with equal thickness and 50 mm radius



**Figure 5.** Absorbed energy vs MVF of plates with equal thickness and 65 mm radius



**Figure 6.** Absorbed energy vs MVF of plates with equal thickness and 80 mm radius

#### 4. Conclusions

In this article, the influence of the MVF on the low velocity impact response of GLARE fiber-metal laminates is studied. Previously published differential equations of motion are employed for this purpose. The considered GLARE plates have equal thickness or equal areal weight and are subjected to low velocity impact under identical impact conditions.

A strong effect of the MVF on the permanent dent depth and energy absorption of the GLARE plates has been found. Considering the same basic lay-up, when the MVF increases, the permanent dent increases whereas the permanently absorbed impact energy decreases.

To the authors' knowledge, no other similar impact study concerning GLARE fiber metal laminates has been published in the current scientific literature. The influence of the MVF on other characteristic values of impact variables is an option for future research.

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