# Chances and challenges in the application of fiber metal laminates

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## Abstract

Fiber-metal laminates (FML) as a combination of metals and fiber reinforced plastic materials are investigated in a variety of current research projects. The intention of combining these two different materials is the compensation of their inherent weaknesses. Certain key parameters for the selection of the constituents of an FML are discussed based on different applications and the related challenges. Therefore, different applications using FML in current research projects at German Aerospace Center are discussed and requirements are deduced. The applications cover UD-CFRP steel laminates, local metal hybridization as well as the use for impact and crash prone structures. The specific challenges in the use of these hybrid laminates like manufacturing and residual stresses are then discussed in more detail as they should also be taken into account when selecting the constituents of an FML for a certain application. Copyright © 2019 VBRI Press.

**Keywords:** Fiber metal laminate, FML, fiber reinforced plastic, residual stress, fiber bragg grating sensors.

## Introduction – 'Intrinsic hybrid laminates'

Marginal fatigue and extraordinary weight-specific stiffness and strength are the major reasons for the use of Fiber Reinforced Plastic (FRP) composites in many lightweight applications. However, as they also show some major weaknesses like low bearing strength or brittle failure properties, FMLs are often investigated with the aim to overcome or compensate these weaknesses. Although many different definitions for FML can be found, the major difference to hybrid structures or composite constructions is that the material combination affects the laminate architecture itself. This means that an FML consists of at least one FRP and one metal layer. Additionally, the term 'intrinsic hybrid laminate' has been established to describe those FML where the cohesion between FRP and metal is created by the FRP matrix during its cure without the use of any additional adhesive.

Unfortunately, it can be observed that FML are taken into consideration for former metal parts which are made of FRP without changing their geometry. This approach is strikingly called 'black metal' design as carbon fiber reinforced plastic (CFRP) is used in the geometry of a metallic part instead of adapting the design to the specific demands of FRP regarding mechanics and manufacturing. Intrinsic hybrid laminates are than employed to compensate the inappropriate design.

As a consequence, a variety of FMLs consisting of different materials are investigated separately to fulfill a specific requirement. The use of FMLs however, is mostly accompanied by a bunch of challenges like surface treatment of the single constituents, special testing due to missing standards, thermal residual stresses, machining - only to name a few – which are often investigated in detail [**1-4**].

Although these challenges are of concern to many material combinations, they are addressed separately. Hence, procedures for a methodical selection of the FML constituents under consideration of the related challenges and maturity are missing. It must be considered that the material properties of an FML do not depend on the material combination only. The material fractions, their orientations and in particular the layer thickness of both constituents are of major influence as well. Even though a methodology is desirable, it is not the focus of the present work. In fact, different applications are discussed with respect to the essential motivation to make use of an FML. In doing so, the related challenges are derived and the two major fields of manufacturing and residual stresses are addressed each in a separate chapter. Therefore own experiments and findings are presented which are however complemented by literature at the appropriate places.

 

***Applications***

The most widespread FML is GLARE, which consists of glass fiber reinforced plastic (GFRP) and aluminum. As aluminum is prone to fatigue, GFRP layers bridge cracks and reduce their progress [**1**]. As especially parts under cyclic tensile load are affected, GLARE is used in upper fuselage panels of the Airbus A380 instead of pure aluminum. GLARE is not certified by authorities in aerospace like a laminate. Instead different GLARE types are approved representing typical laminate lay-ups [**2**] and vary in the orientation of the glass fibers.

Another example for 'intrinsic hybrids' are unidirectional (UD)-CFRP-steel laminates. Especially, in uniaxially loaded parts, the part's notch and impact sensitivity limit the applicable fiber fraction in load direction. As a consequence, the laminates do not achieve their full lightweight potential. Recognizing these limitations, the idea behind UD-CFRP-steel laminates is to reduce these disadvantages by using steel layers with a thickness below 0.08 mm up to a maximum metal volume fraction (MVF) of 12% steel [**3**]. Instead of reducing stiffness and strength, these layers even increase the residual strength of previously impacted parts or specimens. Test results underline an increase of weight-specific stiffness and strength up to 15 % at the same level of residual compression strength after impact [**4**]. In addition, the weight-specific residual compression strength of a laminate with identical damage size is increased [**4**]. The reason for this behavior is a different damage geometry compared to pure CFRP specimen. **Fig. 2** shows the dent depth and damage area for specimens impacted at 9, 12 and 16 J following the AITM1-0010 [**5**] test standard. Different lay-ups are compared. The pure CFRP lay-up, marked "*CFRP-HO-2/0"* in the figure, consists of 8552/AS4 prepreg with a $(0_3/45/\text{-}45)_2/0_3/90/0/90)_s$ lay-up. The other three specimen-types use the same prepreg in a UD-lay-up and interleaved metal foils with 12% steel volume fraction. The metal foils are 0.05 or 0.08 mm in thickness as shown in **Fig. 2** and are distributed in different manners. The steel foils of the UD-St-0.05-outer/12 specimens are distributed more to the outside of the laminate, the steel foils of the UD-St-0.05-inner/12 specimens are distributed more to the inside and the foils in the UD-St-0.08-equal/12 are distributed equally. The results show that the dent depth is reduced when interleaving metal foils, especially with the metal foils being concentrated around the middle layers of the laminate (see **Fig. 2 a**). At the same time the projected damaged area is increased significantly when using interleaved steel foils.

Although the damage area is increased, these impacted specimens show higher compression strength than the pure CFRP reference. This means that not only the damage geometry is influenced by the use of metal foils. Rather the damage tolerance property of the laminate is increased significantly and depends on the lay-up [**4**]. However, the use of these UD-CFRP-steel laminates is most attractive for unidirectional struts, as high strength steel foils are required and their breaking elongation and hence their formability is reduced drastically. Therefore, struts with constant cross-section as show in **Fig. 1** on the top-right are favorable.

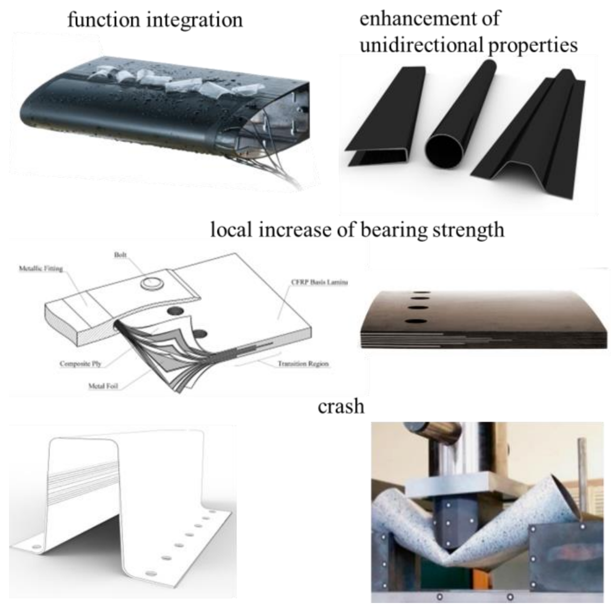


**Fig. 1.** Different applications and reasons for the use of fiber metal laminates at DLR.

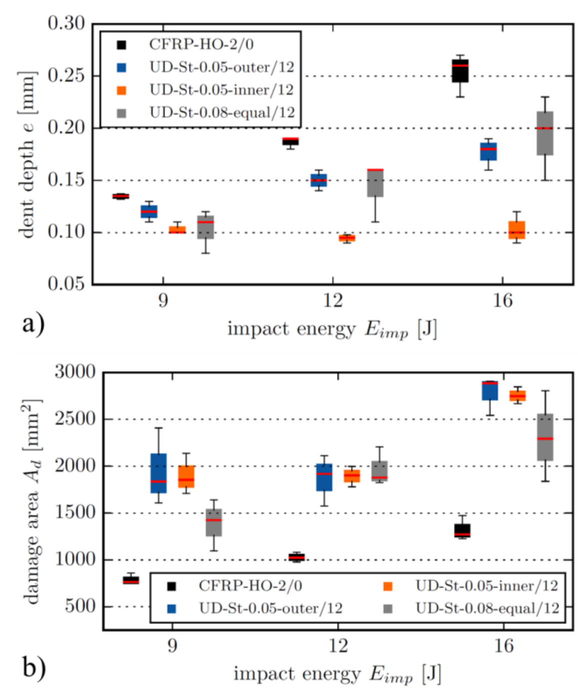


**Fig. 2.** Box plot diagrams for dent depth and damage area of CFRP and UD-CFRP-steel specimens impacted at 9, 12 and 16 J.

Especially under exceptional load cases, the brittle nature of FRP is challenging which may be compensated by the addition of metallic layers. In this way the deformation and failure behavior is adjustable without changing the part`s geometry. The pictures in **Fig. 1** on the bottom-left show a vehicle door sill after bending load test. The results show that load-displacement and failure behavior change basically when introducing metal foils in the laminate.

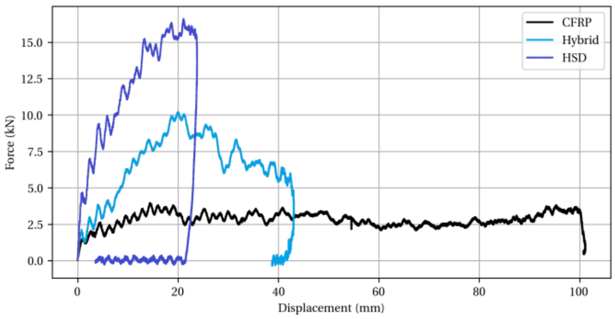


**Fig. 3.** Force-displacement curves of comparable CFRP, HSD and hybrid cylinders under 3-point-bending.

On the bottom-right in **Fig. 1** the arrangement of a 3-point-bending static test is shown as it is used in a drop weight test as well. The investigated specimens are made of CFRP, High Strength and Ductility-(HSD)-steel and a combination of both. In comparison to CFRP and HSD, the lay-up and MVF of the hybrid offers more parameters to adjust the load-displacement curve. In this way, comparably high specific energy absorption is achieved, as shown in **Fig. 3** for three representatives of each material group. Again, constant cross-sections are used for testing, but compared to the previous application; the used steel provides good formability. Hence, more complex geometries may also be achieved.

A further application of FMLs, where the additional metal is introduced locally in an FRP part, is often referred to as local metal hybridization. The reason is the low bearing strength, especially of pure CFRP, which often leads to ramp-ups in the load introduction area. By replacing multiple CFRP layers by titanium or stainless steel sheets, the load carrying capacity is increased. [**6**]. In this way, three different areas are generated: a pure FRP area, a hybrid region with the maximum metal content and a transition region in between the first two areas. By adjusting metal content and design of the transition region, additional ramp-ups are not required in most use cases [**5-8**].

The favorable MVF fraction depends on the used metal, the base laminate of the reinforced part and its loading resulting between 30 and 50%. In this application the distribution of the metal layers, thus the lay-up, is often limited to a few possibilities as the fiber layers oriented along the main load direction are not substituted by metal layers to maintain the good fatigue properties of the CFRP part.

For abrasion protection only one metal layer at the outer surface of an FRP part is required [**9**]. Also a limited number of metallic layers are used when integrating metallic conductive tracks in FRP parts [**10**]. Both applications often lead to asymmetric laminates prone to thermal deformation or the need of additional material layers for insulation purposes. The top-left picture of **Fig. 1** shows a wing tip demonstrator with an electrical heating. The skin structure consists of a woven CFRP layer electrically insulated against the surrounding CFRP structure with the help of GFRP layers and a metallic outer layer to meet the erosion requirements. Thus, the requirements lead to an asymmetrical multi-material lay-up.

All the different applications presented above show that not only the material combination is adapted to each demand, but also the metal volume fraction, the metal layer thickness and the distribution of the metal layers, hence, the lay-up is of crucial influence to fulfill the requirements.

## Fiber metal laminates manufacturing

Strength, delamination and corrosion properties of the laminate essentially depend on the interface between matrix and metal surface. As the metal layers act as a barrier layer against fluids, prepreg is used mostly for the manufacturing of intrinsic hybrid laminates. However, depending on the required flow distance, resin infusion techniques may also be used.

Hence, surface treatment of the metallic foil is a fundamental step in the manufacturing of hybrid laminates. Although a variety of research on the treatment of aluminum and titanium is published, only a few investigations deal with steel.

Solvent cleaning and mechanical cleaning using grit blasting or other abrasive tools such as sand paper, wire brushes or abrasive pads are most common for steel surface pre-treatment [**11-15**]. Solvent cleaning does not modify the surface properties but removes any contaminants. The mechanical abrasion roughens the surface and removes weak and chemically inactive layers [**12, 13**].

Among these methods, grit blasting is the most effective [**16**] and has a clearly visible measure of effectiveness [**17**]. Pickling has produced comparable results to abrasion and grit blasting for thermoset composites. Several acid mixtures have been investigated including nitric-hydrofluoric acid and sulphuric acid [**18, 19**]. These treatments provide adequate dry strength, but durability seems to be quite poor [**13, 20**]. Plasma treatment uses an electrically conductive low-pressure plasma gas consisting of excited atoms, ions and free radicals. The plasma particles react with the surface and each leading to cleaning, removal of material or formation of radicals on the latter [**21**]. Bond strength equivalent to the best chemical treatments was obtained by plasma treatment on titanium [**22**]. Laser treatment is mainly used for the treatment of polymer surfaces. However, it has also been utilized successfully on aluminum and titanium surfaces. Durable bonds were achieved with the patented Ciba laser pretreatment (CLP) for aluminum but also for stainless steel [**23**]. Laser treatment stands out for being environmentally friendly as in the pre-treatment of titanium it replaces chemical and electrochemical processes containing hazardous chemicals such as chromates. The substitution of chemicals containing chromate was also a major driver in the development of sol-gel coatings, mainly based on silane or zirconium, as well [**24-26**]. There are two major objectives for the sol-gel treatment of metal surfaces: to provide good adhesion to organic coatings or adhesives and to increase corrosion resistance. The majority of the processes include hydrolysis and condensation reactions of metal alkoxides of zirconium, cerium, tin or aluminum [**27**]. Finally, a primer may be applied to the substrate surface protecting the surface until the bonding process, to increase wettability of the surface, as a coupling agent or to prevent corrosion [**13**]. Epoxy based primers are mainly used to protect the surface prior to bonding and silane coupling agents are utilized to improve durability of adhesive bonds in the presence of water. However, some primers such as BR127 [**28**] still contain hazardous chromates [**13**].

Thus, different blasting and pickling processes were investigated and a novel vacuum blasting process has been developed as alternative at DLR with the grit particles streaming through two nozzles parallel to the surface [**29**]. Therefore, the coiled metal sheet is conveyed continuously to simultaneously blast both metal surfaces. This approach is used for all the presented work in this paper as it allows to pre-treat the 0.05 mm foils used for UD-CFRP-steel laminates as well as the treatment of 0.2 mm sheets used for local hybridization.

In general, surface treatments are developed empirically and therefore require an evaluation of the adhesion property. Double-lap shear tests as well as 3 and 5-point-bending test are most common [**30**] but the crack energy release rate is also increasingly used for this evaluation [**31**]. It is to be considered that thermal residual stresses superimpose with the actual test load and may falsify the results [**4, 31**]. Although the maximum residual shear stress in longitudinal direction appears outside the loaded area in the bending tests, here, the different single layer stiffnesses in an FML need to be taken into account in the calculation of the interlaminar shear strength (ILSS) when using DIN EN ISO 14130 for example [**32**]. As temperature and moisture content have impact on the laminate's residual stress state, it is recommended to vary these parameters in testing. Vacuum blasting showed significantly higher ILSS for the investigated steel/CFRP interface and promises good potential for automation [**4**].

The feasibility of nondestructive tests for quality supervision purposes is a crucial requirement in almost every part. In aerospace industry, inspection is performed on different levels. Most inspection is done visually with or without any auxiliaries and ultrasonic. Computer tomography (CT) is applied only for very few more detailed inspections. In contrast to pure CFRP, FMLs show dents and failures get detectable on the surface. However, ultrasonic inspection by pulse-echo in FML is limited to a few layers due to the difference in acoustic impedances of both constituents. The high density of the metal also limits the feasibility of CT, as severe streaking artifacts occur as a consequence of incomplete attenuation profiles. Although the overranging can be reduced with special software, a loss of detail around the metal interface remains although different physical filters have been used during testing. Hence, the effort to characterize the failure´s geometry is increased and impedes the better understanding of the involved failure mechanisms.

The investigations revealed that ultrasonic and CT inspections indicate different failure types with different accuracy [**4**]. **Fig. 4** shows the projections of CT and ultrasonic scans as well as the cross-section obtained by CT. The cracks visible in the cross-section can be assigned to the CT projection, whereas the ultrasonic inspection does not detect the fine ends of the cracks. Instead, it detects significantly larger failures in the typical form of delaminations. Hence, it is advisable to combine both inspection methods to achieve a better understanding of the failure mechanisms of FML.

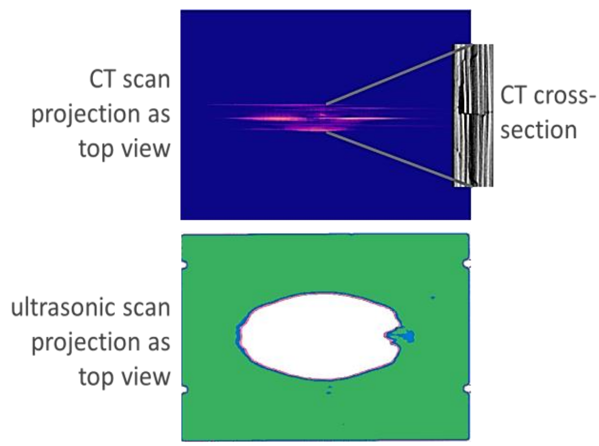


**Fig. 4.** CT and ultrasonic scan projection with CT cross-section of one CFRP-steel specimen after impact.

## Residual stresses

The difference between the matrix's cure temperature and the part's operational temperature, in combination with the different CTEs of the two materials, leads to residual thermal stresses. These residual stresses may also generate deformations in non-symmetrical laminate lay-ups. Different measuring methods are applicable to analyze influential parameters: tensile testing, warping of non-symmetrical bi-material strips, and use of embedded fiber Bragg grating (FBG) sensors as well as strain gauges [**33**]. The FBG sensors consist of a single mode optical fiber with a photo-written Bragg grating in its core corresponding to a periodical modulation of the refractive index. When embedded in the laminate it allows the strain measurement during and after cure. Temperature compensation is performed with the help of additional thermocouples.

FBG sensors reveal the development of the strains during cure and the measurement of the non-symmetric strips allows their quantification. A combination of both methods was developed at DLR where non-symmetric specimens are generated by removing certain layers at room temperature [**33**]. Hence, a calibration of the measured FBG strain during cure is performed based on the curvature of those removed layers at room temperature [**34, 35**].

 

This allows the simultaneous measurement of the strains during the laminate's curing process to develop curing processes with lower residual stresses [**33**]. The experiments are performed on individual coupons with 100 mm width, 200 mm length ad 2.49 to 2.50 mm thickness where all fibers are oriented in longitudinal direction. The steel fraction is 9.6 % with the material data for steel and CFRP provided in **Table 1** [**36, 37**], for more detail see [**34**].

**Table 1.** Material properties steel and CFRP.

| | | steel 1.4310 [37] | CFRP 8552/AS4 [36] |
|---|---|---|---|
| $E_1$ | [GPa] | 165 | 131.6 |
| $E_2$ | [GPa] | 186 | 9.2 |
| $G_{12}$ | [GPa] | 71 | 4.8 |
| $\nu_{12}$ | [-] | 0.3 | 0.318 |
| $\alpha_1$ | [ppm/K] | 16.4 | 0.13 |
| $\alpha_2$ | [ppm/K] | 16.4 | 37.12 |

The reference cure cycle is based on the manufacturer`s recommend cure cycle (MRCC) with a pressure of 6 bar. The manufacturer recommends two heat-up ramps and two dwell stages for HexPly-8552/AS4 prepreg with the first ramp to 110 °C at 2 K/min. After the 60 minute dwell it is heated up again at 2 K/min to 180 °C and cooled down at 2-5 K/min after a hold of 120 minutes. The aim is to connect steel and prepreg at a lower temperature. Therefore, the inertia of exothermal cross-linking reaction is exploited [**38, 39**].

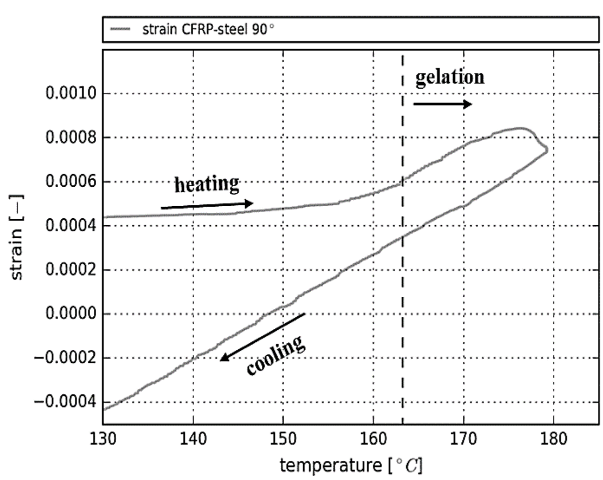


**Fig. 4.** Strain in 90°-direction as a function of cure temperature in a CFRP-steel laminate [34].

The CFRP-steel laminates are equipped with polyimide coated silica glass FBG-sensor positioned in the center of the samples. The gauge length of the Bragg grating is 2 mm and the outside diameter with polyimide coating is 150 µm. The temperature is recorded by K-Type thermocouples also embedded in the laminate. The essential effect is shown in **Fig. 4**, by means of the strain in transverse direction along the temperature. The stress transfer between steel and CFRP during gelation starts where the slope of the curve increases sharply.

To quantify the residual strains, the uncovering method as explained by Prussak *et al.* is used [**34**]. Using MRCC, a residual longitudinal normal stress in the metal layers of 313 MPa is present. By adding the above mentioned cooling step, the normal stress is reduced to 271 MPa – a reduction of 13 %.

## Discussion on material selection

The applications discussed above show that each of them has another motivation leading to different material combinations, MVF and lay-ups. The examples discussed in the manufacturing section introduced some of challenges related especially to FML. Some of these challenges, like NDT, may even prohibit the use of a certain material combination for a particular application although the mechanical properties are advantageous. In addition, surface treatment may increase costs drastically.

As mentioned before, there are no guidelines to support the material selection. The determination of the material properties for certain material combinations depending on the MVF may however deliver a first orientation. With the help of the rule of mixtures or classical laminate theory (CLT) the stiffness and strength can be estimated analytically based on the MVF. As the rule of mixtures does not consider transverse contraction of adjacent layers, it is not recommended for low MVF [**4**].

The weight-specific stiffness and the compressive strength of different material combinations calculated this way are exemplary shown in **Fig. 5** and **Fig. 6** (steel 1.4310, titanium 15-3-3-3 and aluminum 7075 in combination with 8552/AS4 (HTS) and 8552/IM7 (IM) by Hexcel). Both prepregs use the same matrix but different fiber types where IM has higher strength and stiffness.

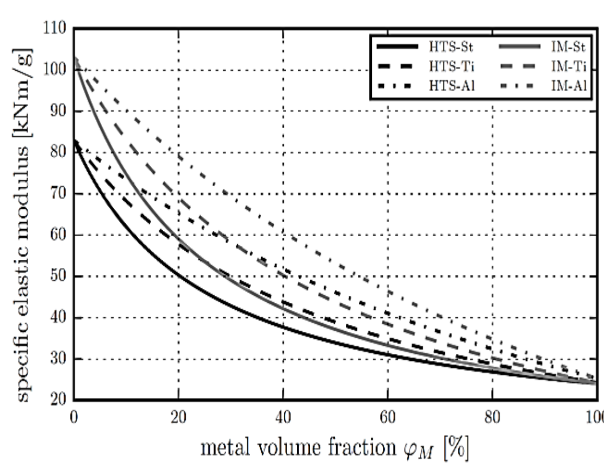


**Fig. 5.** Weight-specific elastic modulus in relation to MVF for steel, titanium and aluminum in combination with HTS- and IM-fiber reinforced plastic.

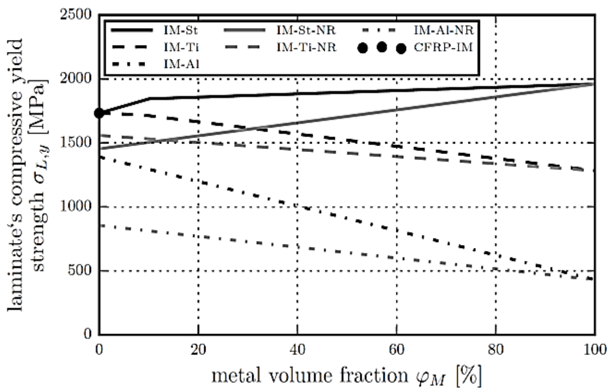


**Fig. 6.** Compression yield strength in relation to MVF with and without (NR) consideration of residual stresses for IM-fiber and strength of pure IM-fiber CFRP.

As most composites show a larger failure strain than the elastic strain of the metals, the yield strength of the latter is the most crucial parameter. Hence, the laminate strength depends on stiffness, MVF, coefficient of thermal expansion (CTE) and the difference between cure and operational temperature [**4**]. **Fig. 5** shows the weight-specific elastic modulus of FMLs consisting of steel, titanium and aluminum combined with both CFRP types. At 0% MVF, pure CFRP properties are achieved. Accordingly, all graphs meet at almost one point at 100% MVF, as all three metals have similar weight-specific stiffness. Calculating the compression yield strength, the residual thermal stresses at room temperature are also considered in **Fig. 6**. A so called ´stress free temperature´ of 180 °C is supposed (166-168 °C meet the standard curing process of the prepreg [**33**]) here. The figure also shows the strength when residual stresses are not considered (grey graphs). The comparison of both cases reveals that the residual stresses have a favorable impact on the compression strength. Hence, the comparably high weight-specific strength of CFRP is maintained only when using low MVF.

Such a simple approach derives many essential characteristics of different material combinations. **Fig. 6** indicates for example that a comparably high compressive strength is achieved when combining CFRP with low fractions of aluminum as a consequence of residual stresses. But at the same time, these stresses significantly lower the tensile strength and prohibit a reasonable use of this material combination.

As discussed in the previous chapter, there are also methods to modify the residual curing stresses which may influence the material selection as well. However, the lay-up and hence the layer thickness is not considered here but has an essential impact on the shear stress being transferred on the interface between the constituents. The shear stress is of great importance when considering thermal stresses but also tensile, compression or bending loads as it also influences crack and delamination propagation. Also the stress itself can be estimated with analytical solutions [**40**] its impact on failure propagation requires experimental investigations. Especially relationships between impact or crash load and failure geometry as well residual strength is predominantly not yet examined.

## Conclusion

Different applications for the use of FML are presented with their related challenges. Although the discussed challenges with respect to manufacturing, NDT and residual stresses are a major concern for nearly all material combinations, they are predominantly investigated with regard to a certain application only. This often prohibits a goal-oriented material selection process as only very simple procedures to describe the basic material properties are available. Hence research on FML with respect to crash, NDT, impact, and durable interlaminar adhesion by experts in the particular fields is desirable.

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### Author’s contributions

Conceived the plan: DS; Performed the expeirments: DS, RP; Data analysis: DS, RP; Wrote the paper: DS. The authors have no competing financial interests.

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