CRASHWORTHINESS OF INTEGRATED CRASH-BOX AND BUMPER BEAM MADE BY DIE-FORMINJG COMPOSITE

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Abstract

The most fundamental and effective means of reach the current co_2 *emission target and end life disposal reduction is through the use of novel light weight and recyclable materials. On the current study, three materials such as, classic glass-mat-reinforced thermoplastics (GMT), GMTex (a chopped fiber glass mat reinforced PP laminate with randomly oriented glass fibers and additionally reinforced with a fabric inside) and GMT-UD, (a chopped fiber glass mat reinforced PP laminate with randomly oriented glass fibers and additionally reinforced with unidirectional oriented glass fiber layers) supplied by Quadrant were considered for front bumper application. Detailed material characterizations were conducted and their applications for substituting the current steel material were numerically assessed. Results shows, modification made on classical GMT is indeed improving both the tensile and impact performance of the original material and therefore can be candidate for structural purpose in place of steel and aluminum.*

1. Introduction

Automobile manufacturing has increased in the last 20 years, reaching about 58 million units (excluding commercial vehicles) in 2000. According to the estimations made by the Organization for Economic Cooperation and Development (OECD), the total number of vehicles in OECD countries is expected to grow by 32% from 1997 to 2020 [1]. This sharp increase in production creates concern on the society, as vehicles impact the environment in several ways throughout their life cycle. On one hand, currently only about 75 percent of end-of- life vehicles, mainly metals, are truly recycled in the European Union. Therefore, the rest (~25%) of the vehicle material is considered waste and generally is burnt or goes to landfills. This generate between 8 and 9 million tons of waste every years in the Community [2]. On the other hand, as the main energy source of automobiles is the direct combustion of fossil fuels, these results in a largest amount of global co_2 emissions. i.e. burning 1 kg of petrol, diesel, kerosene and the like in a vehicle engine leads to approximately 3.15 kg of co_2 emissions. Among the available road transport means, emissions from the ‘‘light duty vehicles’’ i.e. passenger cars and vans are responsible for approximately half of co_2 emissions [3].

Those two major environmental concerns drive law makers to set stricter rules and legislations that limit both co_2 emissions and end life waste disposal of cars.

The EU directive No. 443/2009, established in 2009, legislated that passenger cars should reach co_2 emission targets of 130g co_2/km by 2015 and 95g co_2/km by 2020 [4]. Additional regulations for light commercial vehicles, introduced in 2011, require that they must not exceed emissions of 175g co_2/km by 2017, and 147g $co_2$by 2020. In additions, European Parliament and Council Directive 2000/53/EC on vehicle end-of-life set out specific measures to be put in place by Member States in relation to the collection, storage, dismantling, reuse and recycling of materials and components at vehicle end-of-life. As per this Directive, each Member State is required: to achieve a recovery and recycling target of 95% reuse / recovery by 1 January 2015 (to include 85% materials recycling) and to ensure that all end-of-life vehicles are dismantled, treated and recovered by industry at no cost to the final processor of that vehicle and in a manner that does not cause environmental pollution [5].

The current work is dedicated to assess the design capability of alternative novel materials for one automotive component, bumper beam that can address the above stated problems. Bumper is an important feature of automobiles to prevent or reduce physical damage to the front and rear ends of vehicles during low-speed collisions. In modern passenger car it has to satisfy two main requirements. On one hand, it needs to be deformable enough to absorb as much impact energy as possible so that it will reduce the chance of injury on pedestrian during low velocity collisions and on the other hand it needs to be stiff to protect nearby expensive-to-repair vehicle components such as fenders, hood, light groups, water cooler and intercooler. Therefore the material selection has to address both the above issues.

Random long glass fiber reinforced polypropylene Glass Mat Thermoplastic (GMT) is already used widely by the automotive industry for numerous applications. In the year 2000, 37,000 tones of GMT were used in the manufacture of European automotive components, with a further 19,000 tones being used in Asia and the USA. Current production applications include a number of noise shields and front end structures, as well as the Mercedes A Class rear hatch and double floor structure, the Volvo 850 rear seat structure and Volvo truck dashboards [6]. Kumar and Johnston [7] studied and compared the performance of C- and I-section bumper beams using a variety of compression-moldable, the utilized material was glass-mat thermoplastic (GMT) composite. Gilliard et al [8] developed the I-section beam with 40% (mass fraction) chopped fiber glass GMT. They found that the I-section bumper design has improved static load and dynamic impact performance by using lower cost mineral filled/chopped fiber glass GMT.

Three materials are considered for the current study. A classic glass-mat-reinforced thermoplastics (GMT) i.e. an endless fiber glass mate reinforced PP with randomly oriented glass fibers , GMTex, i.e. a chopped fiber glass mat reinforced PP laminate with randomly oriented glass fibers and additionally reinforced with a fabric inside and GMT-UD, i.e. a chopped fiber glass mat reinforced PP laminate with randomly oriented glass fibers and additionally reinforced with unidirectional oriented glass fiber layers supplied by Quadrant were considered for front bumper application. Detailed material characterizations were conducted and their applications for substituting the current steel material were assessed.

2. Material characterization

Considering the novelty of the proposed material, extensive material characterization has been conducted to obtain the main mechanical properties of the material and to understand the failure mechanism for the intended loading case. Four test program were designed, a tensile test (both longitudinal and transverse directions), a compressive test (both longitudinal and transverse directions), a plane shear test (both longitudinal and transverse direction), and a drop-dart test.

3. Numerical simulation and model description

A nonlinear finite element simulation, with a simplified bumper beam model, as displayed in Figure 1, is carried out using the commercial code ABAQUS/Explicit version 6.12-1. The model comprises three parts, one rigid part, i.e. the impact rigid wall, and one deformable part that integrate crash-boxes and transverse beam and a base cover. The integrated beam is developed form three materials i.e. GMT, GMtex and GMT-UD composite material. A mass of 1,000 kg is rigidly attached at the two rear extremities of the crash boxes, in order to simulate the vehicle mass, and it is allowed to moving with an initial velocity of 4 km/h or 8 km/h towards the rigid wall. Considering the load path, different section has been used at different portions of the proposed structure as shown in figure 1 (b). Hollow tapered truncated square based pyramids are proposed for crash boxes, in order to obtain a progressive failure.

The proposed materials under investigation are compared with the reference material (steel) by two ways:
- Through equal stiffness approach, i.e. , for a given thickness and stiffness of the reference material, the thickness of the targeted material can be approximated by

$$h_x = h_s \sqrt[3]{\frac{E_S}{E_x}} \qquad 1$$

Where h_s *and* h_x are thickness of steel and the targeted material respectively and E_s *and* E_x are the stiffness of steel and the targeted material respectively.

- by direct substitution of the current steel beam by integration of a composite beam with crash box and with minor modifications of the base plate only for joining purpose and using the thickness recommended by the company i.e. ≈ 8mm. During low velocity impact, such as, small parking load, the bumper beam is expected only to bump i.e. it has to operate within elastic limit without any form of permanent damage. Therefore, for the current study, the allowable minimum thickness of the bumper for such small load was determined through monitoring impact energy curve. Having got the threshold value the thickness, it was gradually increased up to a value where the beam gives the similar impact performance as with the reference material and the saved mass was compared.

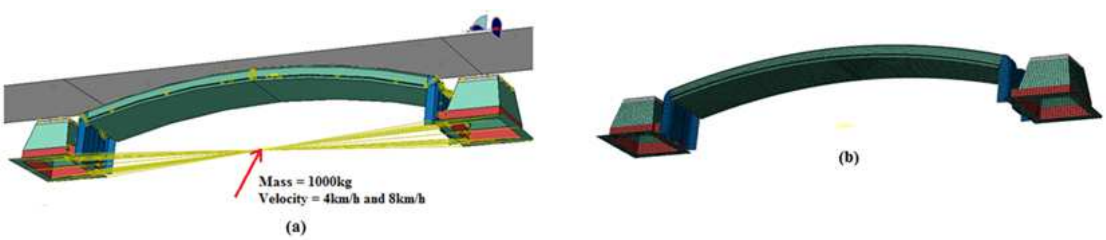

Figure 1: Loading and sections considered for FE modeling

The progressive damage model used in this study is based on the Hashin theory. In this model four different modes of failure are considered, namely, fiber rupture in tension, fiber buckling and kinking in compression, matrix cracking under transverse tension and shearing, and matrix crashing under transverse compression and shear.

4. Results and discussion

4.1 Material data

As stated in the previous paragraphs, the reference material considered were a mild steel with Young modulus E = 206 GPa, density ρ = 7830 kg/m^3, Poisson ratio ν = 0.3, and true stress–plastic strain property as reported [9].

The mechanical properties of the targeted three materials were determined through material characterization. Some of important mechanical properties for finite element simulation are reported in Tables 1. The impact performances of the three materials were compared through conduction of drop dart impact tests at equal energy level. A quasi-static indentation test was conducted with the same test set-up and specimen dimension and then dynamic impact test and the energy required for perforation of the plate was determined.

	GMT	GMT UD		GMTex	
		Longitudinal	Transverse	Longitudinal	Transverse
Tensile strength (MPa)	80,699	180,392	59,213	174,718	70,546
T. Modulus (GPa)	5,810	11,066	6,482	9,241	6,002
T. Poisson's ratio	0,284	0,307	0,217	0,389	0,150
Compression strength (MPa)	65,819	82,183	58,510	68,993	57,102
C. Modulus (GPa)	3,258	5,932	2,637	4,137	2,661
C. Poisson's ratio	0,338	0,430	0,178	0,237	0,168

Table 1. Tensile and compressive property of the considered material s

4.2 Low velocity impact simulation

From our previous related activity, it has been learned that a closed section beam has a better structural integrity and energy absorbing capacity than an open section beam. Therefore, even if an open beam were considered and recommended by the supplier company, for sake of production feasibility and simplicity, with a quick numerical check on the structural performance on the proposed open section beams it was decided to conduct the analysis on a closed section.

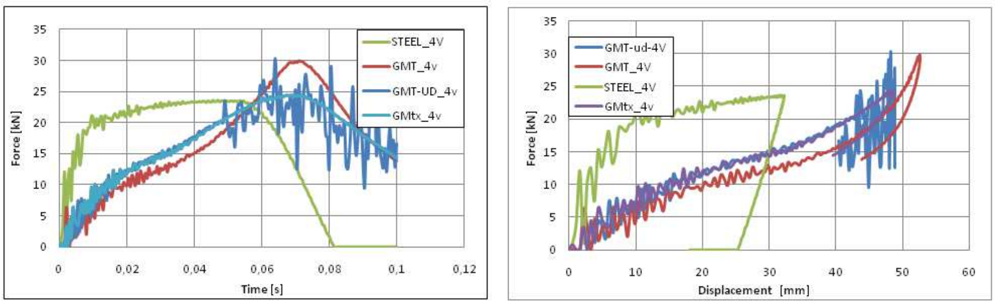

Figure 2 Force vs. time and force vs. displacement curves for the design solutions in steel and in equal thickness of the three considered materials.

The first attempt was conducted by direct substitution of the current steel beam, by integration of the crash boxes and with minor modifications on the base plate only for joining purpose. The thickness recommended by the supplier company i.e. ≈ 8mm has been used. With this thickness, the combined system or the integrated beam- crash box has a mass of 4.69 kg, 4.65 kg and 4.82 kg for GMT, GMtex and GMT-UD respectively. Comparing this mass with that of the reference steel material solution with the same configuration (beam and crash boxes combined) i.e. 7.67 kg, approximately 35% weight will be saved. However, as it can be seen on force vs. time and force vs. displacement curves of the simulation (see Figure 2), all the three material solutions are structurally week. GMT-UD and GMtex show an early sharp break at the center of the beam and GMT shows relatively higher elastic deformation.

Material	Steel	GMT	GMtx	GMT-UD
Thickness [mm]	2.2	7.1	6.1	5.8
Mass [kg]	7.67	3.72	3.32	3.2

Table 2. Thickness and mass of the combined beam- cashbox

The second attempt was made by increasing the section dimension, particularly the base plate. The thickness of the integrated beam- cashbox was determined from the reference material. As described in the previous paragraphs**,** for a given thickness and stiffness of the reference material i.e. (steel), the thickness of the targeted material can be calculated approximately by the relationship indicated on equation 1. Using the proposed expression, the approximated thickness and the mass of the integrated beam- crash box solutions have been calculated as reported in Table 2.

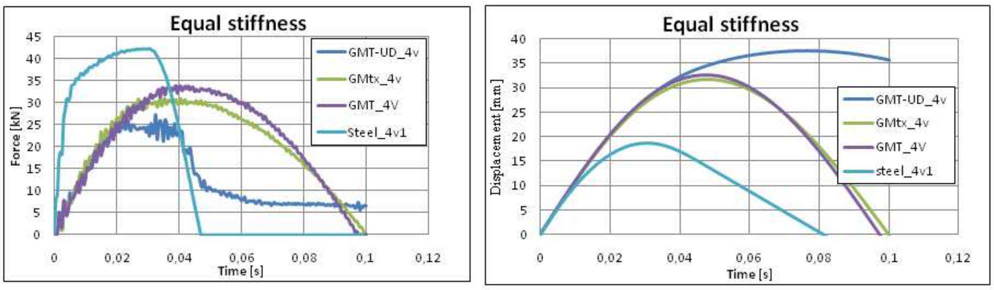

Figure 3: Force vs. time and displacement vs. time curve for the modified bumper system

As presented on table 1, GMT-UD has tensile modules approximately 50% higher than GMT and 25% higher than GMtex, therefore it has a lower thickness. As it was explained in the previous paragraphs, the introduction of unidirectional fibers in both side of the GMT plate, even if it results in improvement in tensile modules, it makes the material relatively brittle. This failure behavior is also observed on energy vs. displacement curves of dynamic drop dart test.

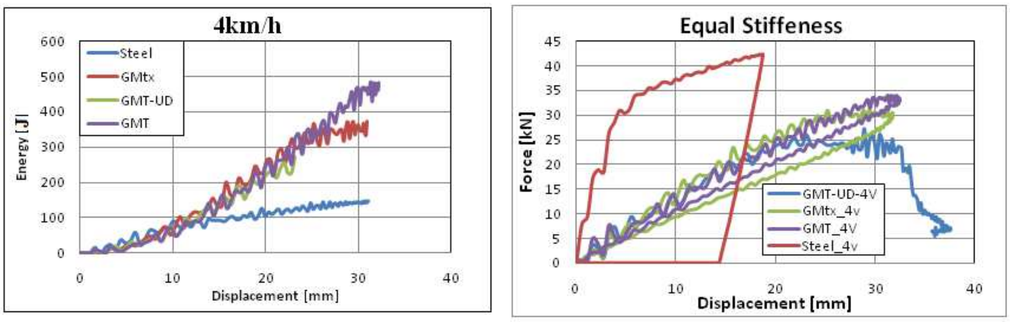

Figure 4: Energy vs. displacement and force vs. displacement curve for the modified bumper system

Through comparing force vs. time and displacement vs. time curves (see Figure 3) of the targeted four materials, GMT-UD has minimum peak load i.e. 25kN, which is one of the important parameters that the designer has to control but it has the maximum intrusion i.e. 37 mm and the beam is totally fractured at the center at the considered impact velocity. The failure behavior can also be tracked using load displacement curve and energy curve as shown in figures 4, 5 and 6.

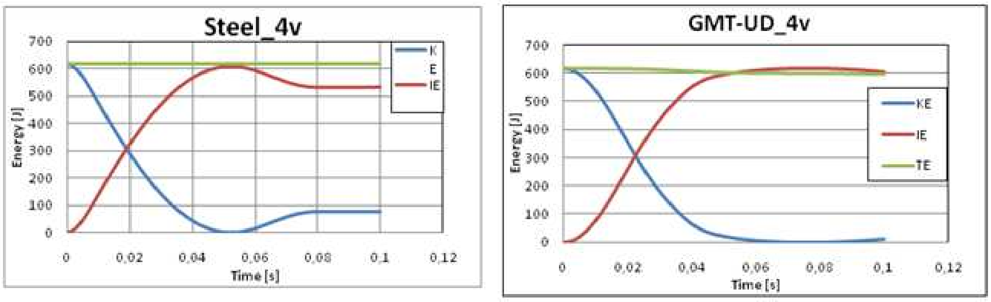

Figure 5: Energy curve for steel and GMT-UD

Both load displacement curve and energy curve of GMT-UD (which shows the amount of energy absorption and the behavior of the impacted system during energy dissipation) confirms that the materials is already fractured at the selected velocity. Similar phenomenon is also observed on the reference material (steel), may due to the strength of the selected steel. As metallic materials have a higher plastic range, the energy curves of steel show the energy dissipation through plastic deformation. Whereas composite materials has very limited plastic range, therefore, energy curve shows that GMT-UD has already passed its elastic limit and, as a consequence, the energy dissipation resulted from the material fracturation .

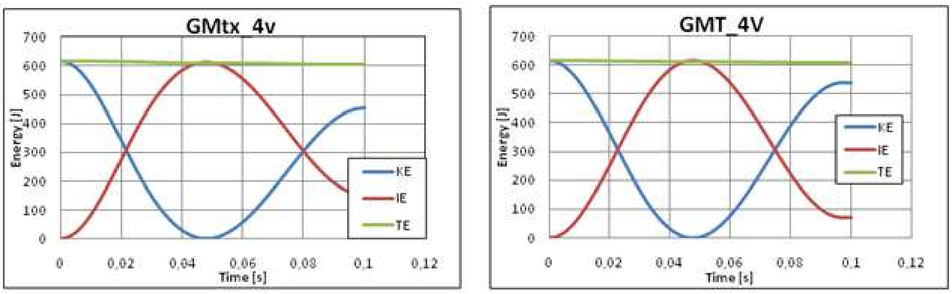

Figure 6: Energy curve for GMtex and GMT

Whereas, both GMT and GMtex are within elastic range, this can be observed from load vs. displacement and energy curves in figures 4 and 6 and their failure mode in figure 7. For 4km/h impact velocity, which is closer to parking load, the bumper have to operate within elastic range, therefore besides bumping and, eventually, a minor cosmetic damage, a complete fracture, as we observed on GMT-UD solution, is not expected. Therefore, with the proposed beam configuration and loading, GMT and GMtex, can be considered for material replacement with significant weight saving.

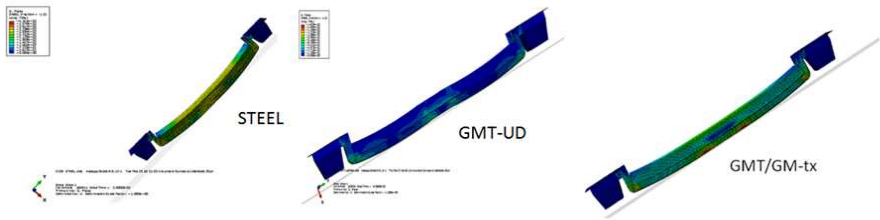

Figure 7: Failure mode of the modified bumper system

Finally, keeping loading and other dimension constant, the above proposed solutions have been also cheeked at higher impact velocity, i.e. at 8 km/h. From force vs. time curve of Figure 8, it can be observed that there are two modes of deformation at this higher velocity, the initial elastic deformation up to ≈ 25-40 kN, that is similar to the behavior observed at low velocity impact i.e. at 4 km/h, and then a complete fracture at the central part of the beam. This fracture leads to a second impact to the other portions of the beam. As it can be seen on the curve, the second impact yields a higher peak load with values of ≈ 170 kN, ≈ 265 kN and 300 kN for GMT-UD, GMT and GMtex respectively.

From the mode of failure of the material and energy curve shown in figures 9 a & b, for the proposed beam geometry, both GMT-UD and GMtex have brittle behavior due to the modification made through reinforcing the classical GMT by woven and unidirectional fibers, and such mode of failure and maximum peak load is considered as a danger input for vehicle occupants, therefore the proposed integrated beam geometry need to be reconsidered.

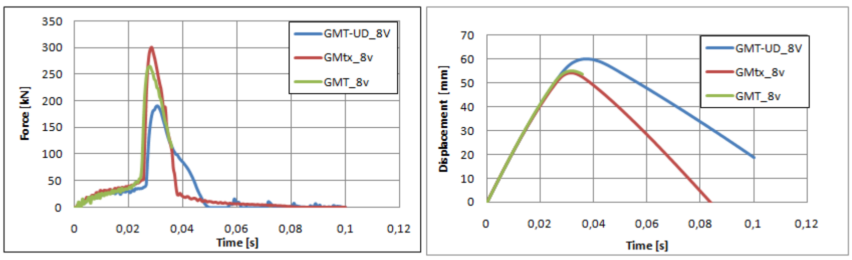

Figure 8: Force vs. time and displacement vs. time curves for the modified bumper system at 8 km/h

In general, the modification made on classical GMT is indeed improving both the tensile and impact performance of the original material and it can be used for structural purpose for some application in place of steel and aluminum as already claimed by the supplier company. However, coming to energy absorbing components, composite materials has completely different failure behavior than conventional metallic material and therefore energy absorbing performance is strongly affected by the geometry of the component. The direct adoption of the traditional metallic energy absorbing geometry may lead to a catastrophic failure and yield higher peak loads. As it has been pointed out in the previous study [10] conducted by the same research group on transversally loaded energy absorbing composite components like automotive bumper beam, a progressive mode of failure can only be obtained through properly optimized beam end profile in such a way that beam corners can serve as stress concentration zone or crack triggering point, so that crack can initiate and progressively propagate along beam longitudinal axis.

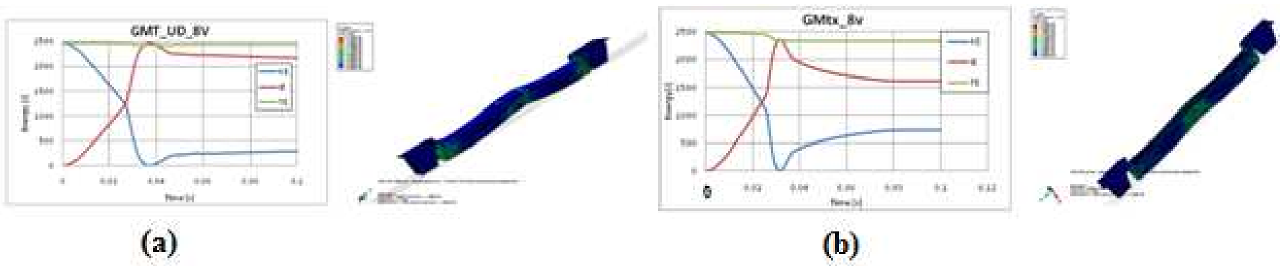

Figure 9 : Energy vs. Time curve and failure mode of GMT-UD (a) and GMtex (b) at 8km/h

5. Conclusions

Alternative novel materials for automotive components have been considered through the application to the vehicle bumper system. , These new materials allow for a different design of the bumper system with an interesting integration of the transverse beam with the two crash boxes. Material characterization and finite element modeling of the integrated front bumper were conducted on three particular materials: a classic glass-mat-reinforced thermoplastics (GMT) _G100F40-F6 i.e. an endless fiber glass mate reinforced PP with randomly oriented glass fibers , GMTex _X111F40-4/1-0/90°X composites , i.e. a chopped fiber glass mat reinforced PP laminate with randomly oriented glass fibers additionally reinforced with a fabric layer inside and GMT-UD_GM20UD20PP-H4 composites, i.e. a chopped fiber glass mat reinforced PP laminate with randomly oriented glass fibers additionally reinforced with unidirectional oriented glass fiber layer. The main observed results can be summarized as follow,

- From material characterization it is observed that the modification made on classical GMT through reinforcing using woven and unidirectional fibers is indeed improving both the tensile and impact performance of the original material and it can be proposed for structural purpose for some applications in place of steel and aluminum as already claimed by the supplier company.
- A dynamic drop dart impact test shows that GMT-UD withstand much more number of impacts before perforation than GMT and GMtex, .At perforation impact GMT priced with similar crack propagation in both transverse and longitudinal axis. This mode of failure is expected since GMT has almost similar mechanical property along the two axes. GMtex has relatively higher crack propagation along one of the axis as there is a significant strength variation between the two main reinforcement directions and the crack is not propagated to a full length of the plate as it will be prevented by the fibers aligned perpendicular to the axis of crack propagation. However, GMT-UD has a full length crack along the axis of unidirectional reinforcement. This failure behavior of GMT-UD combined with its higher fracture and perforation energy performance can be an interest for energy absorbing components because with a proper geometry optimization may serve for developing a progressive failure.
- From numerical study, it has been observed that, for low velocity impact i.e. 4 km/h, as bumpers are expected only to bump, both GMT and GMtex absorb the applied energy through elastic deformation and with tolerable intrusion. Whereas for the selected beam configuration, bumpers modeled by GMT-UD show fracture at the center of the beam. The modification made on a classical GMT trough introducing reinforcement both sides of GMT, particularly at the skin may result in a brittle failure mode.

6. Referance

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