MODAL ANALYSIS OF A LAMINATE PLATE WITH 10 MM NOTCH FOCUSED ON THE EFFECT OF A FUNCTIONALLY ORIENTED FABRIC LAYUP WITH 20 MM WIDE CARBON STRIPS

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ABSTRACT

Functionally oriented fabric (FOF) is a woven textile featuring irregularly distributed secondary material strips in both warp and weft directions, designed to locally improve the mechanical properties of laminates, particularly around openings. This study investigates the impact of different FOF laminate layups on the natural frequencies of laminates with a 10 mm notch. The analyzed layup configurations include [0/90]s, [0/45]s, and [0/30/60]s, with 20 mm wide carbon strips incorporated into the glass fiber structure. The research demonstrates that the FOF structure significantly increases the natural frequencies about 20 % for bending modes of 0/90 layup. About 5 % and almost 30 % for twisting and bending modes respectively in the 0/30/60 layup, and over 20 % and about 40 % for twisting and bending modes respectively in the 0/45 layup. These enhancements help to prevent resonance in standard operating frequencies of mechanisms and machines, thus extending their operational lifespan. Additionally, the strategic placement of functional material strips around structural openings provides increased stiffness without the need for extra layers, effectively reducing the laminate's overall mass. This study highlights the potential of FOF to improve the dynamic performance and lifespan of laminated composite structures used in various engineering applications.

KEYWORDS

Functionally oriented fabrics; Composite material; Modal analysis; Natural frequency; FEA; Circular notch.

INTRODUCTION

Non-woven and woven fabrics are two basic types of fabrics used in composites. They differ in fiber processing. While non-woven fabric has fibers bonded together non-mechanically, woven fabrics are constructed by weaving yarns together. The vertical fibers are called 'warp' yarns, while so-called 'weft' yarns are weaved through the warp yarns along the horizontal width of the textile. Woven fabrics are called textiles. In the weaving process of composite textiles, a yarn is called a roving. The roving consists of straight fibers which are not spun or twisted [1].

Woven fabrics are generally sorted into two groups based on the roving material. In the first case, warp and weft roving is made of the same material. The second type of fabric is so-called 'hybrid fabric', where roving in warp direction consist of different fibers than roving in weft direction, typically carbon-aramid combination. Such a regular alternation of materials in the hybrid fabric leads to homogenization of the properties of the laminate layer. In contrast to these common types of fabrics, the functionally oriented fabric structure (FOF) has irregularly distributed fibers of different materials in the warp and weft (Fig. 1). The base material (BM) predominates in the fabric. Such material is usually cheaper and has worse mechanical properties than the functional one. The functional material (FM) has a minority in the fabric and has better mechanical properties and therefor it is in principle more expensive than the base material. The advantage of a FOF is the efficient use of expensive material with high mechanical performance quality.

The production of a functionally oriented fabric structure allows lamination without cutting the continuous fibers in the layer and so having better mechanical properties at the same time. FOF is intended for using in the layup to locally improve mechanical properties to increase strength or stiffness in required area. The suitable applications are laminates with holes for fasteners, or with openings such as windows or mounting openings providing access to machine parts under the laminate part [2]. Other application is a large format laminate in which the strip of functional material weaved in the fabric acts like a 'shell rib'.

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Figure 1. Example of functionally oriented fabric (FOF).

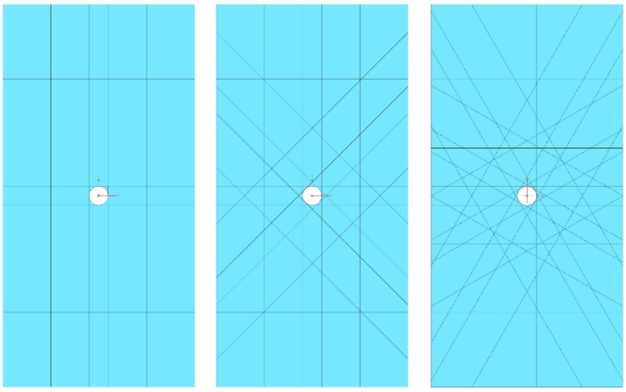

Figure 2. CAD model of FOF laminate layups: [0/90], [0/45] and [0/30/60].

The aim of this work is to determine first four modes of selected layups of FOF laminate. To evaluate natural frequencies of analyzed laminates and compare the obtained results. Finally, the conclusion of the effect of FOF layup on the natural frequency of a laminate with a notch will be made. The work is a continuation of the FOF parameter analysis. The presented results serve to the performance description of a FOF laminate.

LAMINATE

There are three regions of material type in sense of warp and weft roving combination in FOF laminate: glass-glass, glass-carbon (or carbon-glass) and carbon-carbon. The base material E-glass EC13 272 Z20 T63C roving is combined with the functional material carbon Tenax E HTA 40 E13 6K roving. Both are present in warp and weft directions in the way they form locally stiffened areas, as shown in Fig. 1. Both materials belong to the standard modulus materials. Glass fiber modulus is 71 GPa and carbon fiber modulus is 220 GPa. Mechanical properties of a laminate are estimated by theoretical elastic models [3] with use of an epoxy resin system with a modulus of cured system of 3 GPa.

A dimension of an analyzed plate is 100×200 mm (width×length). The size of a notch in the center of the plate is 10 mm. Thickness of the plate is given by its layup. The layups are [0°/90°]s, [0°/45°]s and [0°/30°/60°]s, see Fig. 2. A CAD model of the simulated specimen includes pads areas, as it would be in a real test setting. The purpose of the pads is to prevent a damage in the testing machine jaws. It clearly defines the area of load and constraints application in the simulation. The width of the carbon strips is 20 mm. FOF laminate simulation results are compared to results of base material only (glass) laminate with the same layup orientations and the notch size.

MODAL ANALYSIS

The parametric finite-element model of a functionally oriented fabric laminate is created by the ply-based modelling method. The woven fabric lamina is defined by software as three layers of unidirectional fibers (UD). Two outer layers of UD (warp) and one intermediate layer of UD rotated by 90° (weft). Material orientation plays an essential role in proper composite material definition. Each material region must have a correctly defined system of coordinates to respect an orthotropic character of composite material.

In general, the first step in solving the dynamic properties of a structure is the determination of natural frequencies and mode shapes by performing a modal analysis of a free body without external load and any constraints. If damping is neglected, the results of such a simulation are real eigenvalues and normal modes. The first six modes have zero frequency, which corresponds to the six degrees of freedom of freely constrained (unconstrained) body. For typical material damping values of laminates, the damping does not significantly influence the natural frequencies and mode shapes. The damping reduces the vibration level near resonance.

DISCUSSION

A plate laminated by standard process has layers of glass fabric and strips of carbon fibers in extra layers. That makes laminate thicker, which means heavier. The thickness in notch area is almost doubled. The mass of laminate plate with extra carbon strips is 0.08098 kg. The same size plate made of FOF with 10 mm notch has mass of 0.0488 kg. The difference is 40 % of total mass. The bigger size the plate is, the higher the absolute value of mass saving is. Another issue is the laminate symmetry and its A-surface quality. Laminate made of FOF has uniform thickness and can be made in a closed mold to get A-surface on both sides of the part.

The shapes of first four non-zero modes are shown in Fig. 4. First two are twist and bending of the laminate plate. The shapes of modes for glass only laminates and for FOF laminates are the same. The results differ only in displacement and frequency values.

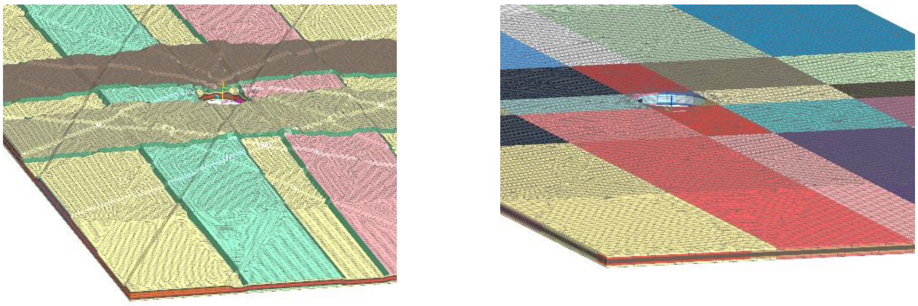

Figure 3. A FE model of laminate with carbon strips in extra layers (left) and a laminate made of FOF (right).

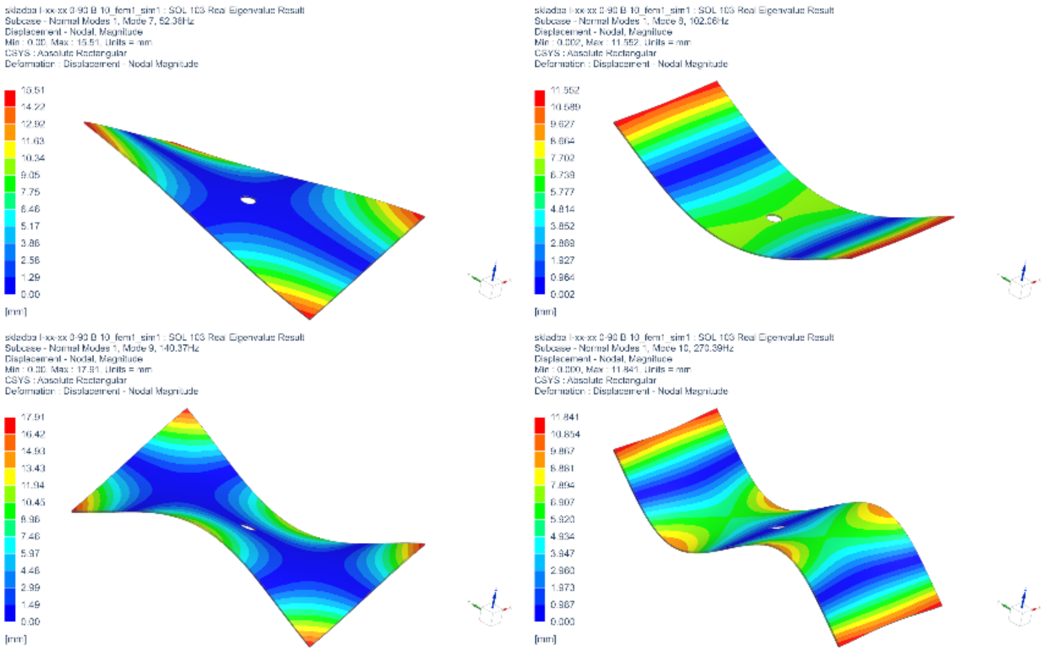

Figure 4. A FE model of laminate with carbon strips in extra layers (left) and a laminate made of FOF (right).

Table 1. Natural frequencies (Hz) of a plate with a 10 mm notch.

	[0/90]s			[0/45]s			[0/30/60]s		
	Glass	**FOF**	**Δ %**	**Glass**	**FOF**	**Δ %**	**Glass**	**FOF**	**Δ %**
1st mode	54.24	52.36	-3.5	63.60	79.32	24.7	103.6	116.8	12.7
2nd mode	80.33	102.1	27.1	78.16	111.6	42.8	114.1	148.0	29.7
3rd mode	137.6	140.4	2.0	152.6	187.4	22.8	241.9	268.0	10.8
4th mode	223.0	270.4	21.3	217.0	299.8	38.2	316.6	393.8	24.4

Natural frequencies of the mentioned four modes are summarized in Table 1. A glass-only and a FOF laminate plate are in the form of three layups. Significant benefit of carbon fiber strips in 0/90 layup is in second and fourth mode, which are the bending modes. Carbon strips make the plate frequency to increase about 27 % and 21 % in second and fourth mode respectively. The strips oriented in longitudinal and transverse direction increase the bending stiffness in 0/90 layup more than in twisting. That is consistent with the theoretical assumption. According to increase of natural frequency in 0/45 layup with carbon fiber strips, that layup is most efficient in the increase in stiffness of all three analyzed layups. The growth is over 20 % for first and third mode (twisting), and about 40 % for second and fourth mode (bending). 0/30/60 layup has higher frequencies than 0/90 layup, but lower than 0/45 layup. That corresponds with the theory, as it respects the dependency of mechanical properties on fiber orientation.

The frequency growth for 0/30/60 FOF layup is more than 25 % in bending modes and about 10 % in twisting modes compared to glass-only laminate. Frequency growth in bending modes is almost the same as for 0/90 laminate layup. Higher frequencies are in comparison of twisting modes.

CONCLUSION

The functionally oriented textile structure (FOT) or functionally oriented fabric (FOF) is a 2D woven fabric material for manufacturing of continuous fiber laminates. It is a type of fabric with non-randomly irregularly distributed threads of fibers of functional material. The benefit of such a woven structure are effectively distributed material properties in the specific areas where the best material performance is needed. Predominant material are low-cost fibers with average mechanical properties. Such a material is called a based material (BM). BM is combined with a functional material (FM), which has very good mechanical properties. FOF allows to reduce the number of layers in layup as there is no need to puzzle cuts of different materials. That can help to reduce waste in mass production. The carbon fiber placement in warp and weft direction, strip width and span of strips can be modified during weaving process of FOF according the application requirements.

FOF structure helps to increase natural frequency of a laminate, which prevents standard operating frequency mechanisms and machines to reach the resonance. The functional material strips within the structure and especially around a structural opening (hole) helps to stiffen the laminate and the opening edge respectively. Speaking about resonance and stiffening the opening edge, the FOF has a potential to prevent the resonance of a mechanical joins, which can extend the joins' lifespan.

The results of simulations are consistent with the theory and show the potential of functionally oriented fabrics usage. The laminate layup customization allows tuning of laminate properties according to mode shape. Strips of functional material oriented in a longitudinal material direction have high effect on the bending modes. Strips angled from a longitudinal direction effect the twisting modes.

Analysis of FOF laminates with modified parameters are planned in the future to describe material performance and particular applications. After the evaluation of model with experimental data, simulations of FOF material in specific applications are going to be performed.

Acknowledgement: *This publication was supported by the Ministry of Industry and Trade (MPO) within the framework of institutional support for long-term strategic development of the research organization - provider MPO, recipient VÚTS, a. s.*

REFERENCES

1. Woven vs. non-woven. JPS Composite materials, 2021, online: https://jpscm.com/blog/woven-vs-non-woven-fabrics/ [cit. 25.04.2024]
2. Zbončák R.: Finite element model of a laminate made of functionally-oriented fabrics. In: Doubrava, Karel, Kristýna Kubášová, Zdeněk Padovec, Milan Růžička a Radek Sedláček. Experimental stress analysis 2022. Book of extended abstracts. Prague: Czech Technical University in Prague, 2022, pp. 144-145. ISBN 978-80-01-07010-9.
3. Zbončák R.: Elastic properties prediction models of continuous fibers composites: composite materials. Liberec: VÚTS, 2018. ISBN 978-80-87184-81-3.