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EFFECT OF STRAIN RATE ON STATIC ELASTIC RESPONSE OF GLASS-POLYESTER COMPOSITE. PART 2: ANALYSIS OF EXPERIMENTAL RESULTS

This paper is the second part of a study aimed at evaluating the influence of the strain rate of a plain weave GFRP laminate in a non-destructive static three-point bending test on the stress response of the material. It was found that the stress level during the entire course of the deflection rises with the increase in the strain rate. The relative change in the stress level is comparable for the 0/90 and 45/-45 samples. As the loading speed increases, the elastic modulus of the material also grows. For an increment in the strain rate from 1.11·10^{-3} to 5.57·10^{-1} 1/s, the increase is 10% for the 0/90 samples and 17.7% for the 45/-45 samples. The dependence of the modulus on the strain rate is logarithmic. Based on the theoretical analysis, the cause of the observed effects of the strain rate on the material response was attributed to the viscoelastic behavior of the matrix (cured polymer resin) and the viscoelastic behavior of the system of fibers at the level of the laminate mesostructure.

Keywords: glass-polyester laminate, static bending, strain rate, normal stress, elastic modulus in bending, energy dissipation

INTRODUCTION

This paper is the second part of a study aimed at evaluating the effect of the strain rate on the stress response of a plain weave GFRP laminate in static non-destructive three-point bending tests. The first part of the study contained the methodology of non-destructive bending tests and details of determining the two characteristics subjected to analysis: the modulus of elasticity and the energy dissipation of the load-unload cycle. These characteristics were adopted as comparative criteria for assessing the impact of the strain rate on the mechanical response of the material. It should be emphasized that taking up the problem and the developed methodological approach is of a pioneering nature. An overview of the results and conclusions are presented below.

RESULTS AND DISCUSSION

The basis for the analysis of the effect of the strain rate on the material response are the deflection curves determined at different rates of the loading bar (i.e. different strain rates – the conversion is given later in the text). The curve sets are shown in Figures 1 and 2.

For both sample directions (0/90 and 45/-45), one can see an evident increment in the stress level with the increase in the loading rate. The curves for individual speeds show a slight scatter, but the series do not overlap. Therefore, the trend is clear.

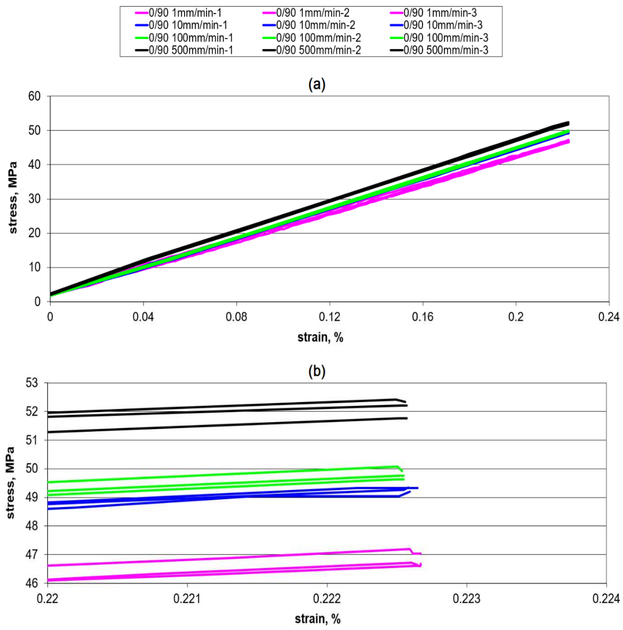

Fig. 1. Bending curves of samples at different loading rates – samples in 0/90 direction: a) full course of curves, b) zoom of curves where differences caused by different loading rate and actual spread of curves are clearly visible

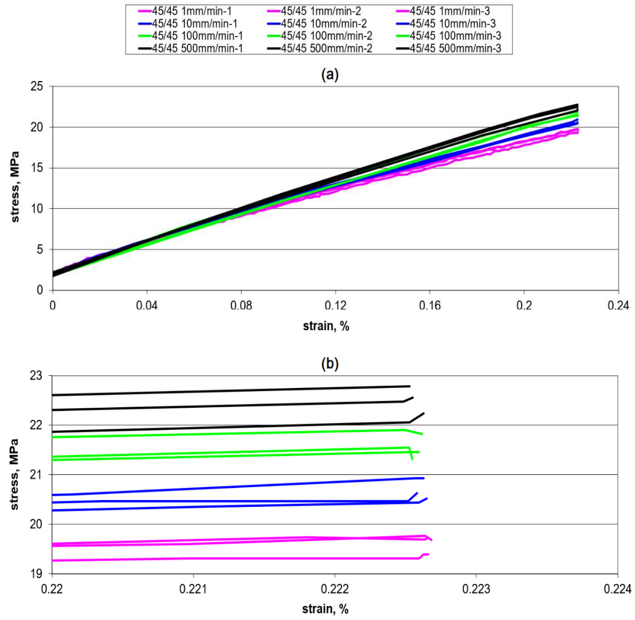

Fig. 2. Bending curves of samples at different loading rates – samples in 45/-45 direction: a) full course of curves, b) zoom of curves where differences caused by different loading rate and actual spread of curves are clearly visible

Notes on course of bending curves

It should be noted that the deflection test itself is subject to uncertainty. It results from the instability of the measurement caused by the inertia delaying the start-up, the looseness of the measuring device, but above all, the imperfection of the geometry of the samples (surface unevenness, warping). Especially at the beginning fragments of the curves – for individual types of samples it is from 0.5 to 0.7 mm deflection – their disturbances are visible, as shown in Figure 3. In the further sections, the course stabilizes; only at the end of the course (where the system measurement "brakes") can another disturbance be seen (see Figures 1b and 2b).

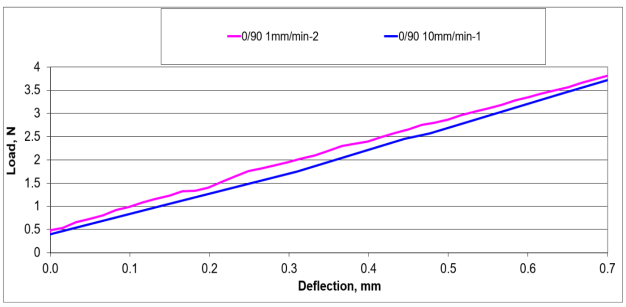

Fig. 3. Disturbances in course of load-deflection curves of laminate samples – on example of 0/90 samples bent at loading rates of 1 mm/min and 10 mm/min

It is worth noting in Figures 1-3 that the curves corresponding to the low deflection velocity reveal greater disturbances in the course and they are visible throughout the curve. Although in the initial section they are the largest, the curve for 1 mm/min in Figure 3 runs even above (i.e. at a higher load level) the curve for the speed of 10 mm/min; a change in the trend takes place at higher deflections (Figs. 1 and 2). The greater effort of the drive mechanisms of the measuring device, obtained at higher speeds, probably reduces the impact of potential clearance and local braking caused by the friction of the mechanisms or shape imperfections of the cooperating parts. Hence the more stable course of the curve. An additional issue is the smaller number of measurement points for higher speed, which causes "optical smoothing" of the curve. The observed disturbances in the course of the curves clearly indicate that drawing conclusions from the initial area of the curves (i.e. taking data from there to determine the modulus) would be burdened with an additional error.

The *elastic modulus* and the *energy dissipated in the load-unload cycle* were selected as two comparative criteria, allowing analysis of the studied issue of the effect of the strain rate on the stress in the material for the assumed population of samples. A comparative analysis of these two characteristics is presented below.

Elastic modulus

As a rule, it is assumed that the modulus of elasticity is a constant property of the material. However, it changes depending on the temperature, and based on the few literature reports [1, 2], the strain rate of the material. The results of the modulus determined on the tested samples at different strain rates (the determination methodology was described in the first part of the study) are presented in Tables 1 and 2.

TABLE 1. **Modulus of elasticity of epoxy-glass fiber laminate at different strain rates obtained in bending tests (flexural modulus) – sample direction 0/90**

Bending rate [mm/min]	Strain rate [1/s]	Flexural modulus E_g [MPa]
1	$1.11 \cdot 10^{-3}$	9955(210)
10	$1.11 \cdot 10^{-2}$	10529(79)
100	$1.11 \cdot 10^{-1}$	10798(59)
500	$5.57 \cdot 10^{-1}$	10950(112)

TABLE 2. **Modulus of elasticity of epoxy-glass fiber laminate at different strain rates obtained in bending tests (flexural modulus) – sample direction 45/-45**

Bending rate [mm/min]	Strain rate [1/s]	Flexural modulus E_g [MPa]
1	$1.11 \cdot 10^{-3}$	3638(23)
10	$1.11 \cdot 10^{-2}$	4038(338)
100	$1.11 \cdot 10^{-1}$	4075(99)
500	$5.57 \cdot 10^{-1}$	4283(33)

The obtained data are also presented graphically together with the approximation function (logarithmic approximation gives R^2 at a level above 0.9) – the versions of the graphs with logarithmic approximation are shown in Figures 4 and 5; the original version is included in the appendix to the first part of the study.

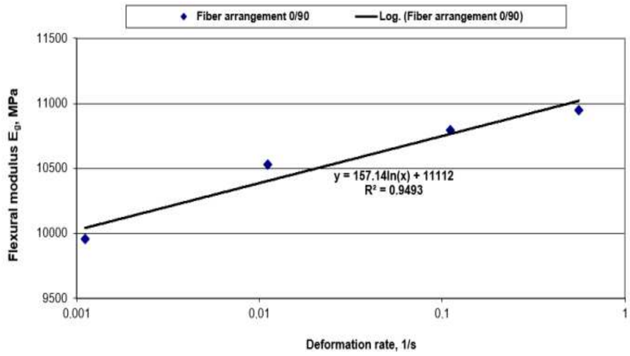

Fig. 4. Diagram of changes in modulus of elasticity E_g of epoxy-glass laminate with strain rate – arrangement of fibers in sample direction 0/90

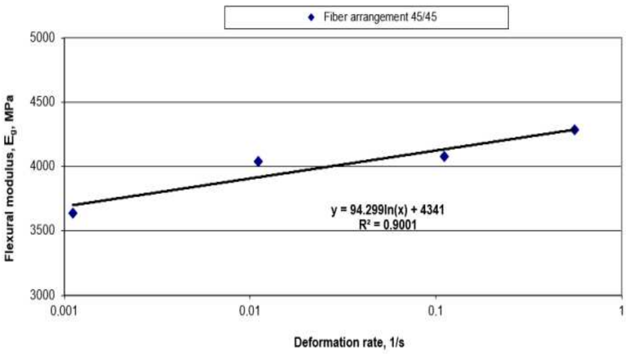

Fig. 5. Diagram of changes in modulus of elasticity E_g of epoxy-glass laminate with strain rate – arrangement of fibers in sample direction 45/-45

The obtained results allow us to conclude that in the polymer-fiber composite laminate, the strain rate clearly affects the mechanical response of the material. The resistance of the material to the stress input (expressed by the modulus of elasticity) grows with the increase in the strain rate. The results in Tables 1 and 2 and Figures 4 and 5 indicate a logarithmic increment in material resistance with an increasing strain rate.

Analysis of energy dissipated in load-unload cycle during bending

The method of determining the energy of the load-unload cycle during non-destructive bending tests was described in detail in the first part of the study. The determined energy values are presented in Table 3.

TABLE 3. **Energy dissipated in load-unload cycle determined during non-destructive bending for sample directions 0/90 and 45/-45, at bending rate of 1 and 500 mm/min**

Sample	Bending rate (strain rate)	Average energy [mJ]
0/90	1 mm/min ($1.11\cdot10^{-3}$ 1/s)	0.732(0.131)
0/90	500 mm/min ($5.57\cdot10^{-1}$ 1/s)	0.429(0.004)
45/45	1 mm/min ($1.11\cdot10^{-3}$ 1/s)	1.191(0.141)
45/45	500 mm/min ($5.57\cdot10^{-1}$ 1/s)	0.724(0.121)

The obtained results allow us to conclude that in the polymer-glass fiber laminate, the strain rate clearly affects the energy dissipated during the loading-unloading cycle in the elastic range. The amount of dissipated energy is smaller at a higher deformation rate – with a 500-fold increase in speed, the dissipated energy is reduced by approx. 40%. Greater values of dissipated energy for the 45/-45 sample direction than for the 0/90 indicate a greater share of the matrix and local movement of the fibers in the energy dissipation process, compared to the straining of the fibers alone.

Discussion of obtained results

Fiber composites should exhibit behaviors that are the resultant of the elastic properties of the fibers and the viscoelastic-plastic cured resins [3, 4]. In the investigated composite, the fibers are the main load-bearing component. Nevertheless, the effects observed at different strain rates undoubtedly result mainly from the presence of a viscoelastic polymer matrix and from the local displacement of fibers and their mechanical impact on this matrix. In an excellent model description of the laminate structure [5, 6], and even in descriptions that take into account its mesostructure [7, 8] (i.e. strands of fibers, knots, crimping, etc.), fibers are treated as remarkably elastic areas of the material volume. In the analyzed composite, they fill about half of this volume. Taking into account the directional distribution of the fibers (cross arrangement), we conclude that during bending they will occupy approx. ¼ of the working cross-section. Taking into account the modulus of elasticity of glass fibers (E-glass) and cured resin, the ratio is about 100:1. Theoretically, the influence of the matrix on the deformation of the material in the elastic range is only a few percent. However, the observed effects of material resistance at different strain rates indicate a much more significant influence of the matrix. The observed change in modulus of elasticity is logarithmic (Figs. 4 and 5). It proves that the impact of the mechanisms causing the demonstrated trend of increasing the resistance of the material with strain rate decreases in the higher values of the strain rate, which would be impossible in the case of a material with only elastic properties. Due to the complex nature of the internal structure of the studied type of composite and the participation of the polymer in this structure, it would be reasonable to attribute the observed effect of the strain rate on the response of the material to its viscoelastic properties.

For analysis purposes, the viscoelastic response of a material can be conventionally divided into two components: an *elastic component* and a *viscous component*.

The elastic component will consist of the elastic response of the fibers and the elastic component of the viscoelastic response of the matrix. In theory, elastic deformation is modeled with a virtual spring, the resistance of which grows linearly with the increase in deformation [9]. The behavior of such a model is completely independent of the strain rate. Of course, a real spring has mass, so accelerating its parts relative to each other with different speeds requires correspondingly different forces (according to the 2nd and 3rd laws of motion [10]). In the case of elastic deformation, the equivalent of a spring is the elastically displaced fragments of the continuum of the deformed material. Although this justifies a general increase in energy input for the process of elastic (and not only) deformation of materials at a higher speed, it does not explain the effects observed in this study. This is because the acceleration of the loading system only occurs at the very beginning of the test and is not taken into account when analyzing the results. The entire analyzed part of the strength test runs at a strictly defined loading speed. The fact that every material exhibits viscoelasticity – including solid metals and ceramics [11, 12] is justified. Nonetheless, these effects are very subtle and do not represent a level sufficient to explain the results obtained in this study. Therefore, it should be assumed that the elastic component of the material resistance has no significant effect on the change of the total material resistance with the change in strain rate.

The viscous component of the deformation response of the composite will mainly contain the viscous component of the deformation response of the matrix and the resistance resulting from local imperfections in the structure of the reinforcing fibers. The viscous component of the matrix deformation response is a factor nonlinearly dependent on the deformation rate, as it is associated with conformational mechanisms [13, 14]. These mechanisms include the imposition of irreversible changes in the polymer chains, such as the friction of adjacent segments, as well as the breaking and restoration of physical bonds, with the reversible effects of the elastic stretching of chemical bonds. This results in a non-immediate reversibility of these mechanisms. Moving fragments of matrix polymer chains, even in a relatively small (elastic) range, is associated with overcoming highly stochastic stretching and rotation paths, with mutual jamming and pressing against each other. The pressure can cause local chains to be connected by Van der Waals forces (the strength of the connection depends on the distance between the connecting atoms in the sixth power [15, 16]). The local formation of new bonds and their breaking is a phenomenon that may proceed non-linearly in time – both the formation and breaking of the bond require the application of force for a certain time [17]. It should be emphasized that the local breaking and reconstruction of physical bonds is strongly limited in the studied case owing to the glassy state of the polymer. A certain nonlinear contribution to the resistance of the laminate during its deformation in the elastic range can be attributed to the fibers: at the level of the mesostructure of the laminate, they form a complex system of strands and interlacings (cross-reinforcement). Structures of this type show viscoelasticity in themselves [18]. Thus, the meso-structured strands of fibers are surrounded by a matrix, both directly within the strands and in the spaces between the strands. They also surround areas rich in matrix material, so-called "resin pockets" [19]. Deformation of the laminate is associated with forcing local displacements of such strands of fibers, e.g. when bending the strands of the fibers will tend to straighten in the stretched part of the beam and to buckle in the compressed part [20]. In both cases, they will cause straining of the surrounding viscoelastic polymer matrix, which will determine the non-linear deformation response of the material.

The logarithmic course of the change in the resistance of the material with the changing strain rate proves the simultaneous influence of both of the above-mentioned deformation components (elastic and viscous) of the material, the effect being different at different deformation rates. At lower rates, the conformational mechanisms (viscous component) probably have a slightly greater impact. At higher velocities, these mechanisms do not keep up with the occurrence and we are dealing with a smaller impact on the course of changes. This can be explained by the ability of the material to manage energy through the operation of various types of mechanisms. "Purely elastic" mechanisms manage energy only through direct elastic storage; this is an action independent of time (both at a low and high deformation rate, the displacement by a given section will absorb the same amount of energy). In the case of viscous mechanisms, we deal with the absorption (dissipation) of energy, mainly through friction and breaking/creating physical bonds. These processes are time dependent. Increasing the deformation rate for these processes will be associated with a significant rise in resistance, which will require an increase in energy input, and at the same time, on a macro scale, will result in a local increment in stress, i.e. "stiffening" of this local deformation system. This in turn does not cause it to deform inelastically, but transfers the load, allowing only elastic mechanisms related to the change in the distance between molecules and atoms, or conformational movements of chain segments within the range limited by the resistance of adjacent segments. Of course, when a certain level of stress is exceeded, the material is destroyed [21, 22], and the growth in the strain rate reduces the deformability of the materials.

The hysteresis loops recorded for the load-unload cycles (presented in the Appendix to the first part of the study) clearly indicate that the tested material does not exhibit entirely linear behavior as part of elastic deformations, and is characterized by an evident absorption of energy not contributing to the elastic return. This confirms the probable occurrence of the mechanisms described above. The value of this energy – see Table 3 – is approximately half as high for a low strain rate (order 10^{-3} 1/s) than for a high one (order 10^{-1} 1/s). The level of the value of the energy is also about half higher for the laminate deformed in the 45/-45 direction than for the 0/90 direction (regardless of the deformation rate). The combination of these two effects indicates that the viscoelastic mechanisms described above, related to the matrix and the fiber-matrix interaction at the mesostructure level, are the main cause of mechanical energy dissipation in the load-unload cycle. They are also undoubtedly the main reason for the variation in the mechanical response of the laminate to the change in the strain rate.

As mentioned in the first part of the study, the analyzed issue should not be combined with DMA type tests (dynamic-cyclic tests). In this study, the overlapping effects resulting from short-term strain repetition were avoided, which is contrary to DMA methodology [23]. It should be emphasized, however, that DMA studies are (usually) also carried out in the elastic range of deformations, and at the same time they clearly prove the dissipation of mechanical energy in this range of deformation [24, 25], which confirms the assumed justifications of the results obtained within this study.

CONCLUSIONS

- The stress level during the entire course of the elastic three-point bending test of the composite sample grows with the increase in the loading rate.
- For the sample direction 0/90, the influence of the strain rate on the stress response of the material seems to be greater than for the 45/-45 one. However, taking into account the difference in the level of stresses recorded in the tests (the stresses for the 0/90 direction are approx. 2.5 times higher than for 45/-45), it can be concluded that this effect is comparable for both the tested directions of fiber arrangement.
- As the loading speed increases, the elastic modulus of the material also increases. These changes for the loading rates 1 - 500 mm/min (corresponding to the strain rate range $1.11\cdot10^{-3}$ - $5.57\cdot10^{-1}$ 1/s) are 10% of the initial modulus value in the case of sample direction 0/90 and 17.7% in the case of 45/-45. The dependence of the modulus on the strain rate is logarithmic.
- Theoretical considerations indicate that the main cause of the observed changes is the viscoelastic behavior of the cured polymer matrix of the studied composites. Nevertheless, the observed effects cannot be justified by the matrix operation alone – the viscoelastic effects must also apply to the reinforcing material of the composite, in particular at the level of the mesostructure. Due to the preliminary and pioneering nature of the conducted research and the limited volume of the publication, it did not include attempts to experimentally prove the occurring mechanisms causing differences in the stress and elasticity of the materials for different strain rates. Explanation of these mechanisms, resulting in raising the importance of the obtained results, will require further research.
- It should be emphasized that the influence of the strain rate of the material on the stress arising during elastic deformation is a very interesting issue with both cognitive and practical potential. Further research on this issue seems to be sensible.

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