Danuta Witemberg-Perzyk[1]
Warsaw University of Technology, Institute of Mechanics and Design, Narbutta 85, 02-524 Warsaw, Poland

Anna Boczkowska[2], **Zbigniew Pakieła**[3]
Warsaw University of Technology, Faculty of Materials Science and Engineering, Wołoska 141, 02-507 Warsaw, Poland

INFLUENCE OF LOADING COURSE ON FAILURE STRESS OF GLASS FABRIC REINFORCED POLYCARBONATE COMPOSITE

Tensile strength of woven glass reinforced composites with polycarbonate matrix was investigated. Several types of loading programs were examined: monotonic with different strain rates, monotonic with preceding loading up to different values of the stress and subsequent unloading, creep at several constant load levels preceded by fast monotonic loading. Additionally, the composite matrix structural changes at the composite failure were monitored through measurements of the degree of whiteness (fogging) occurring in the matrix material.

The experimental results have pointed out the basic types of the course of loading or deformation in which the history effect on failure stress is significant for the examined material. It was found that unloading, i.e. stress relief, has no remarkable influence. Significantly lower failure stresses were obtained for the loading programs which included creep at constant load, compared to all other cases, which revealed similar failure stress values. In particular, the change of strain rate, within the limits of two orders of magnitude in simple monotonic loading tests, had practically no influence on failure stress.

The degree of whiteness of the matrix in creep tests was significantly higher compared to both fast and low rate monotonic loading tests, however no regularity was observed for the tests which included unloading. It is concluded that the phenomena associated with matrix damage may significantly influence the strength of the investigated composite. A further research, aimed at explanation of the creep effect on the composite failure stress, is necessary.

Key words: **glass fabric-polycarbonate matrix composite, failure stress, loading program**

WPŁYW PRZEBIEGU OBCIĄŻANIA NA NAPRĘŻENIE NISZCZĄCE KOMPOZYTU O OSNOWIE POLIWĘGLANOWEJ WZMACNIANEGO TKANINĄ SZKLANĄ

Przedmiotem badań była wytrzymałość na rozciąganie kompozytu o osnowie z poliwęglanu wzmacnianego tkaniną z włókien szklanych. Zbadano szereg typów programów obciążania: monotoniczne z różnymi prędkościami odkształcenia, monotoniczne ze wstępnym obciążeniem do różnych wartości i odciążeniem, pełzanie przy różnych poziomach stałego obciążenia poprzedzone szybkim obciążeniem. Dodatkowo śledzono zmiany strukturalne w osnowie poprzez pomiary stopnia zbielenia (zmętnienia).

Wyniki doświadczalne wskazały podstawowe typy przebiegów obciążania lub odkształcania, przy których wpływ historii na naprężenie niszczące jest dla badanego materiału znaczący. Stwierdzono, że odciążanie nie ma zauważalnego wpływu na naprężenie niszczące. Znacząco niższe wartości otrzymano natomiast dla tych programów obciążania, które obejmowały pełzanie przy stałym obciążeniu, w porównaniu do wszystkich innych przypadków, dla których uzyskiwano zbliżone wartości naprężeń niszczących. W szczególności zmiana prędkości odkształcania w granicach dwóch rzędów wielkości praktycznie nie miała wpływu na wartość naprężenia niszczącego.

Stopień zbielenia osnowy w próbach pełzania był znacząco wyższy w porównaniu do prób, w których stosowano obciążania monotoniczne, zarówno z małą, jak i dużą prędkością odkształcania, jednakże nie zaobserwowano prawidłowości dla prób obejmujących odciążanie. Można sądzić, że zjawiska związane ze zniszczeniem osnowy mogą istotnie wpływać na wytrzymałość badanego kompozytu. Stwierdzono, że niezbędne są dalsze badania w celu wyjaśnienia wpływu pełzania na naprężenie niszczące kompozytu.

Słowa kluczowe: **kompozyt tkanina szklana-poliwęglan, naprężenie niszczące, program obciążania**

INTRODUCTION

The mechanical behavior of polymer composites can be greatly influenced by their time dependent properties [1-6]. Moreover, it is generally recognized that the course of loading (or deformation) in time can significantly influence failure stress values of many materials, including metals at elevated temperatures, polymers and other non-metallic materials, due to so-called history effects. In a previous work [7] it has been showed experimentally that strain or load history can have substantial and varied influence on the yield behavior of glassy polymers, particularly on the time to yield. Because of the known relationship between the time to yield and stress, it is obvious that the yield stress assumed for a desired time of loading depends also on the course of straining or loading. In particular,

[1, 2, 3] dr inż.

the following three phenomena were observed: material softening induced by a viscoplastic flow, softening due to unloading including its possible development with time, as well as hardening induced by straining in opposite direction.

The appearance of history effects in glassy polymers suggests that also strength of composites with polymeric matrices can be sensitive to the history of loading since the yielding of the matrix can affect the whole matrix-reinforcement system. In the present work the appearance of history effects which could be possibly expected in tensile testing of the polymer composites is examined.

MATERIAL

The material chosen for investigation was a woven thermoplastic composite. The systems of that type are currently appearing as potential advanced materials in many engineering applications [8, 9]. The reinforcement used was a glass fabric of the 8H-Satin type style 7581, supplied by Hexcel. That type of fabric structure is symmetrical in two orthogonal directions and is widely used for many structural composites. The matrix was a polycarbonate in a form of foil type Macrofol, supplied by Bayer. The composite plates 340x480 mm were made of fabric layers aligned in one direction and interleaved with PC films, giving the total thickness 2 mm and fiber volume content 55%. The plates were manufactured by Institut fur Verbundwerkstoffe GmbH, Kaiserslautern in Germany, by the static press processing.

The choice of polycarbonate as a matrix material was influenced by the fact that the authors have an experience in mechanical behavior of that material, including the above mentioned history effects. It was also expected that the mechanical contribution of the relatively tough matrix will be significant so that similar effects may appear in composite behavior.

EXPERIMENT METHODS AND DESIGN

The specimens were cut from the composite sheets along the fibers direction. A number of preliminary tests have led to the following final design of the specimen: uniform width 15 mm, total length 160 mm; the grip tabs 40 mm long were made of pure polycarbonate plates 2 mm thick and glued to the composite specimen with a specialized adhesive.

All the mechanical tests were carried out on the MTS model 810 machine, which allowed arbitrary load or cross-head displacement programming in time. The elongation was measured with a 50 mm gauge length extensometer.

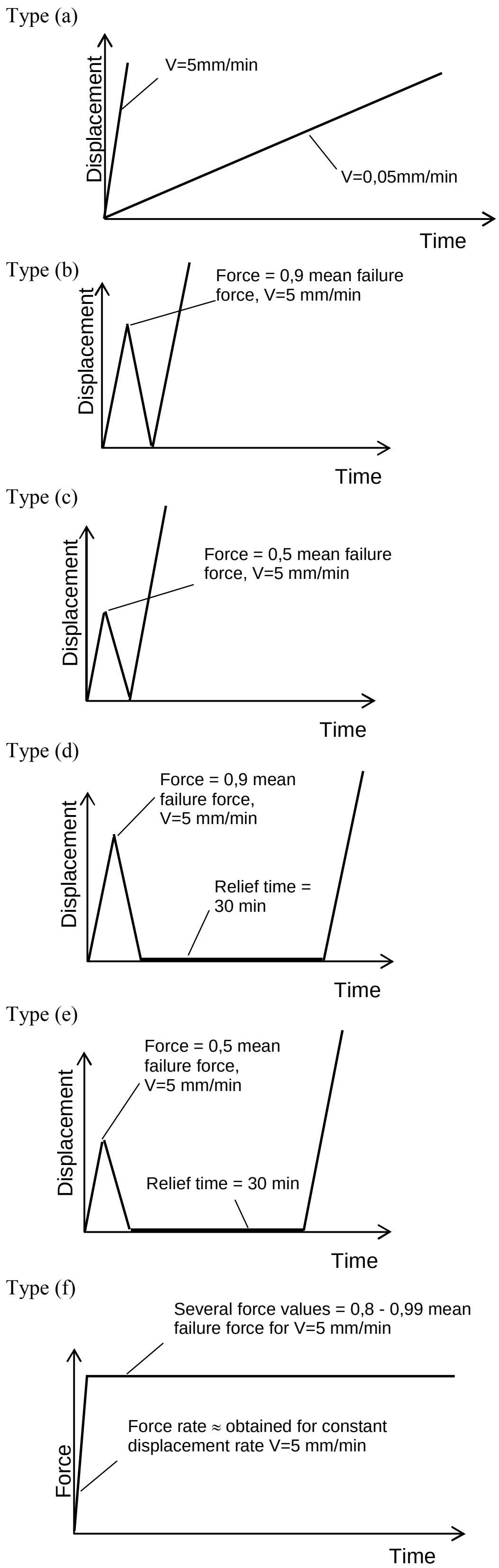

Fig. 1. Types of loading programs applied in tensile testing of the composite: types (a) v = 5 mm/min and (b), (c), (d), (e) - recognition of the unloading effects; types (a) and (f) - recognition of the time effects; v denotes machine cross-head displacement rate

Rys. 1. Typy programów obciążania zastosowane w próbach rozciągania kompozytu: typy (a) v = 5 mm/min oraz (b), (c), (d), (e) - badanie skutków odciążania; typy (a) i (f) - badanie przebiegu obciążania w czasie; v oznacza prędkość ruchu trawersy maszyny wytrzymałościowej

A number of loading programs were applied as illustrated in Figure 1. The choice was motivated by the analysis of the characteristic possible loading courses which may appear in practice as well as some of the results obtained previously [7].

Additionally, the PC matrix yielding at the composite's failure was recorded through measurements of the degree of its whiteness (fogging). This was obtained from the macro photographs of the non damaged regions of the cracked specimens, by an image analysis program. Three square fields of the size 60x60 pixels were selected randomly from such area, both for the cracked and a new specimen (also photographed in the same conditions, for a reference) and the relative whiteness can be defined by an index defined as

$$I_w = \frac{\left[\sum_{i=1}^{3}\sum_{gsv=1}^{255} gsv \times n_{gsv}\right]_{\text{cracked}}}{\left[\sum_{j=1}^{3}\sum_{gsv=1}^{255} gsv \times n_{gsv}\right]_{\text{new}}} \qquad (1)$$

where gsv is the gray scale value for a given pixel obtained from the image analysis program (ranging from 0 - black to 255 - white) and n_{gsv} is the number of pixels having that gray scale value. Thus the proposed whiteness index, having values > 1, is insensitive to variations in illumination.

EXPERIMENTAL RESULTS

In Figure 2 a photograph of a typical damaged areas of specimens is shown. In Figure 3 exemplary pictures of non-damaged areas of a cracked and a new specimens are shown.

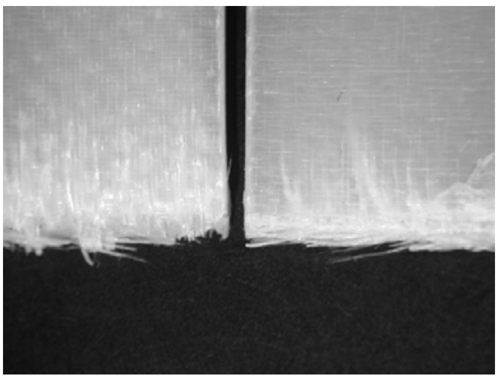

Fig. 2. Exemplary specimen failure area

Rys. 2. Przykładowy obszar zniszczenia próbki

In Figure 4 two exemplary stress-strain curves are shown. Their shapes are typical for woven fabric polymer composites, including the characteristic knee point [10]. It is worth noticing that the slopes of the curves were much similar, irrespective of the strain rate.

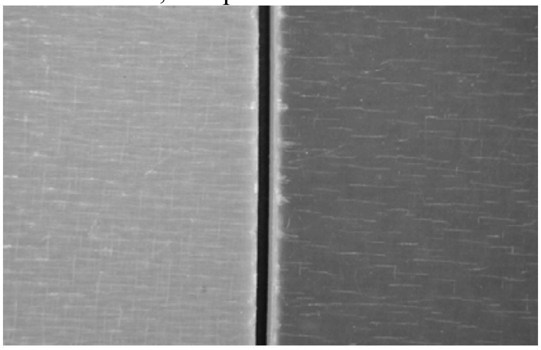

Fig. 3. Exemplary areas of cracked (left) and new (right) specimens; that types of pictures were used for calculation of the whiteness indices

Rys. 3. Przykładowe obszary zniszczonej (lewa strona) i nowej (prawa strona) próbki; tego typu obrazy używano do wyznaczenia wskaźników zbielenia

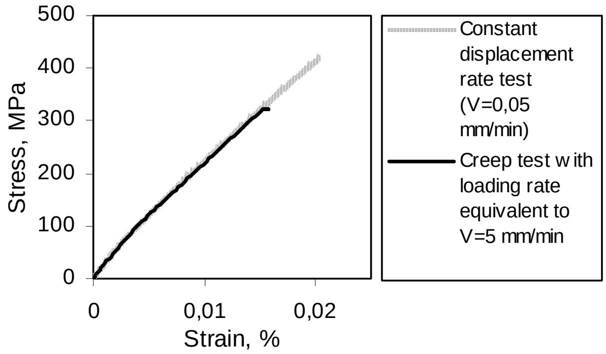

Fig. 4. Exemplary stress-strain curves of the composite

Rys. 4. Przykładowe krzywe rozciągania badanego kompozytu

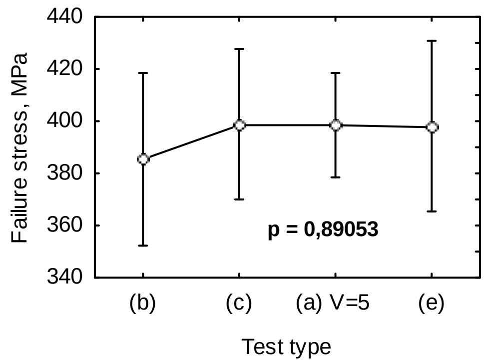

Fig. 5. Results of the ANOVA obtained for the tests dedicated for the recognition of possible unloading or relief effects; the test types are explained in Figure 1; the vertical bars represent 0.95 confidence intervals

Rys. 5. Wyniki analizy wariancji (ANOVA) otrzymane dla prób wykonywanych w celu stwierdzenia występowania skutków odciążania; oznaczenia rodzajów prób objaśniono na rysunku 1; pionowe słupki oznaczają 0,95 przedziały ufności

The comparison of the failure stresses obtained in the tests aimed at the recognition of possible unloading or relief effects (detailed programs shown in Figure 1) is presented in Figure 5 in the form of the ANOVA results. That type of statistical analysis facilitates objective estimation of the dependence between two or more categories of data (test types in our research). The unquestionably large p-value indicates that the observed differences in failure stress are insignificant in this case.

In Figure 6 the comparison of the failure stresses obtained in the tests aimed at the recognition of possible time effects (detailed programs shown in Figure 1) is presented. The unquestionably small p-value indicates that the observed differences in failure stress are significant. It is also clear that only the differences between creep tests and constant displacement (strain) rate are essential, independent on the rate value, while the rate itself is not significant.

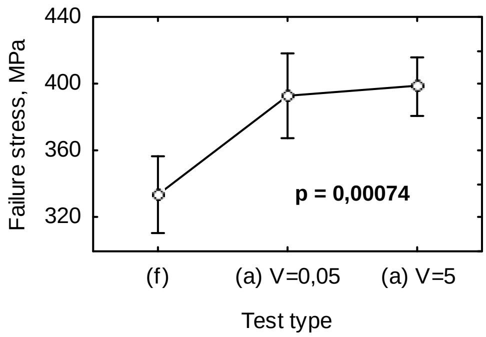

Fig. 6. Results of the ANOVA obtained for the tests dedicated for the recognition of possible time effects; the test types are explained in Figure 1; the vertical bars represent 0.95 confidence intervals

Rys. 6. Wyniki analizy wariancji (ANOVA) otrzymane dla prób wykonywanych w celu stwierdzenia występowania efektów czasowych; oznaczenia rodzajów prób objaśniono na rysunku 1; pionowe słupki oznaczają 0,95 przedziały ufności

In Figure 7 two representative time-strain curves obtained for the two test types described in Figure 6 are shown. It can be supposed that the differences in failure stress can be attributed to the different course of straining in time, i.e. the history effects.

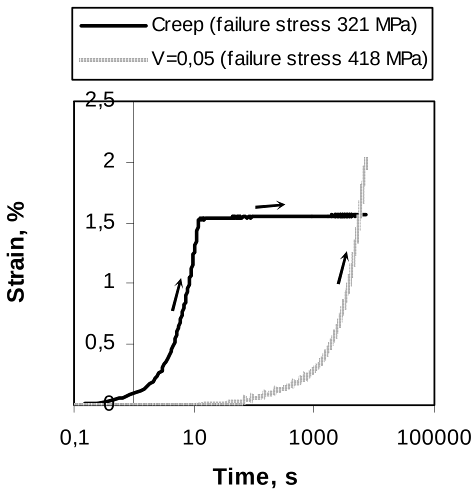

Fig. 7. Two exemplary time - strain curves of the composite (for explanations see Fig. 4); arrows indicate the differences in courses of straining between curves

Rys. 7. Przykładowe dwie krzywe odkształcania w czasie badanego kompozytu (objaśnienia podano na rys. 4); strzałki wskazują na różnice przebiegów odkształcania w czasie występujące między krzywymi

In general, the cause of the strain history effects is a development of different material structures during deformations taking place with different rates at different stages or at different stress levels. In the present case it can be stated that the small creep deformation which starts after reaching the constant stress level in the test type (f), has an extremely large impact on the weakening of the material, leading to its failure at a significantly low stress value. It should be noticed, that the long time of straining itself does not give that degree of material's weakening.

Although polycarbonate was found to exhibit strain history effects [7], the contribution of the matrix to the observed effect in the composite is unknown. Some guidance could be obtained from the tests in which the degree of the matrix structure changes at the composite failure is captured. In Figure 8 the summary of the whiteness index measurements is shown.

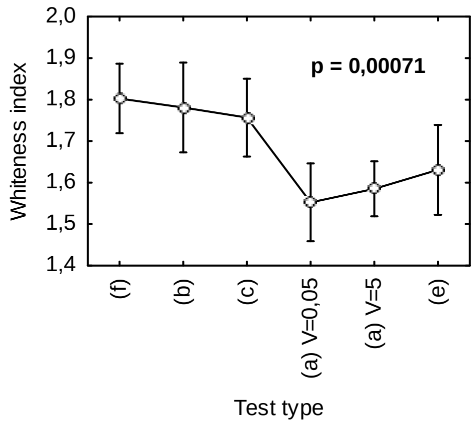

Fig. 8. Results of the ANOVA obtained for the whiteness tests; the test types are explained in Figure 1; the vertical bars represent 0.95 confidence intervals

Rys. 8. Wyniki analizy wariancji (ANOVA) otrzymane dla badań zbielenia; oznaczenia rodzajów prób objaśniono na rysunku 1; pionowe słupki oznaczają 0,95 przedziały ufności

The results are not univocal. The small p-value indicates that the observed differences of the whiteness indices are indubitably significant and the largest differences are observed between the test types which have also given the largest differences in failure stress levels, i.e. monotonic tension (a) and creep (f). This would indicate a significant role of the matrix. However, similar whiteness indices were obtained for creep tests (f) and tension tests with unloading types (b) and (c), which also differ much in the failure stress values.

CONCLUSIONS

The experimental results have indicated the basic types of the course of loading or deformation in which the history effects on failure stress are significant for the examined material. It was found that unloading, i.e. stress relief, has no remarkable influence. The comparison of creep tests at constant stress level with constant strain rate tests revealed that reaching the same values of elongation at similar times may result in significantly different failure stresses.

Because the composite is a complex system, structural interpretation of the observed phenomena is difficult. The observations of the whitening due to strain induced changes in the polycarbonate matrix suggest that its properties can have a remarkable contribution to the composite failure stress. Further tests, aimed at elucidation of the observed behavior of the composite are planned, with an application of acoustic emission technique.

REFERENCES

[1] Jayaraman R., Fracture criteria to predict creep rupture of polymers and polymer composites, TRIP (Elsevier) 1997, 5, 116-122.

[2] Cardon A.H., Qin Y., Van Vossole C., Bouquet P., Prediction of the residual structural integrity of a polymer matrix composite construction element, Mech. Time-Depend. Mater. 2000, 4, 155-167.

[3] Bocchieri R.T., Schapery R.A., Experimental methods for characterizing the time-dependent behavior of fiber composites with growing damage, Proc. Offshore Technol. Conf., Huston, USA 2000, 3, 355-364.

[4] Raghavan J., Meschii M., Creep rupture of polymer composites, Composites Sci. Technol. 1997, 57, 375-388.

[5] Moore R.H., Dillard D.A., Time-dependent matrix cracking in cross-ply laminates, Compos. Sci. Technol. 1990, 39, 1-12.

[6] Miyano Y., Nakada M., Muki R., Applicability of fatigue life-prediction method to polymer composites, Mechanics of Time-Dependent Materials 1999, 3, 141-157.

[7] Witemberg-Perzyk D., Wytrzymałość czasowa polimerów termoplastycznych przy obciążeniach przemiennych, Mat. X Seminarium Tworzywa sztuczne w budowie maszyn, Kraków 2003, 417-420.

[8] Mariatti M., Nasir M., Ismail H., Effect of sample cutting direction on mechanical properties of woven thermoplastic prepreg, Polymer Testing 2000, 19, 617-624.

[9] Leach D.C., Continuous fiber reinforced thermoplastic composites, (in:) I.K. Partridge (ed.), Advanced composites, Elsevier, London 1989, 43-111.

[10] Osada T., Nakai A., Hamada H., Initial fracture behavior of satin woven fabric composites, Composites Structures 2003, 61, 333-339.

Recenzent
Stanisław Mazurkiewicz