Journal of Reinforced Plastics
and Composites
http://jrp.sagepub.com/

Hysteresis Measurements for Characterizing the Dynamic Fatigue of R-SMC

R. Renz, V. Alstadt and G.W. Ehrenstein

Journal of Reinforced Plastics and Composites 1988 7: 413
DOI: 10.1177/073168448800700502

Published by:
SAGE
http://www.sagepublications.com

Hysteresis Measurements for Characterizing the Dynamic Fatigue of R-SMC

R. RENZ
Daimler Benz AG
Stuttgart, West Germany

V. ALTSTÄDT AND G. W. EHRENSTEIN
Institut für Werkstofftechnik
University of Kassel
West Germany

ABSTRACT

Objective of the investigations is the determination of the dynamic fatigue behaviour of sheet moulding compounds (SMC) by the application of a very precise hysteresis measuring method. The influence of material composition such as glass content, amount of filler, resin toughness, etc. on the dynamic fatigue behaviour of R-SMC is of special interest.

An advantage of the hysteresis measuring method is the possibility of determining a non-dimensionalized damping quantity for non-linear viscoelastic material response, which reacts very sensitively as an overall damage criterion to structural changes in SMC with progressing fatigue. An important conclusion from hysteresis measurements is the high sensitivity of the material damping to variation of the composition of a sheet moulding compound. An increase of the amount of filler or glass causes a fundamental increase of the damping level, since there are more interfaces in the material where static friction or sliding friction occurs. An increase of the material damping by interface friction as a result of micro-crack formation or micro-crack growth characterizes the beginning of the micro-mechanical damage progress. The micro-crack formation mainly starts at the interface between the resin and the filler particles due to the poor bonding of the filler particles, which are without any coupling agent to the matrix.

INTRODUCTION

GENERALLY THE FATIGUE behaviour of polymers is described by Wöhler-diagrams in accordance with classical construction materials. Despite rigorous testing, cycles to failure revealed this way give no hints about structural

---

This paper was presented at the 41st Annual Conference, Reinforced Plastics/Composites Institute, The Society of the Plastics Industry, Inc., 1986.

0731-6844/88/05 0413-22 $4.50/0

changes connected with the fatigue. Moreover, a variety of publications show that no fatigue limits can be found either on homogeneous or glass fibre reinforced composites [1].

With R-SMC as an example it will be shown here how fatigue behaviour can be described completely by use of careful instrumentation of a servo-hydraulic test system and what conclusions about the damage process can be made.

SMC's are very damage-sensitive because of the heterogeneous composition. As causes of damage in fibre-reinforced composites the following factors are known:

- debonding of matrix-fibre interface
- debonding of resin to filler interface
- matrix cracking
- pull-out of fibres or fibre-bundles
- fibre fracture due to tensile fracture or fibre buckling

With SMC, cavities of up to 1 mm originating from the shrinkage of the resin have to be considered.

The properties of SMC's are determined by the composition of the material as well as by process parameters. Therefore it is important to know how different material composition, for example, glass-fibre content, filler-content, low shrinkage additives and resin toughness influence the mechanical properties.

While modification of composition with regard to static loading are discussed extensively in the literature [2,3], only preliminary investigations of the influence of material composition on dynamic fatigue behaviour have been conducted [4,5].

EXPERIMENTAL

Hysteresis Test Procedure

On cyclic loading, viscoelastic material behaviour induces a hysteresis in the stress-strain diagram. The variation of the hysteresis-loop with progressive material fatigue is what is measured by hysteresis measurements, and can be described by a number of characteristics. Of special interest are the form of the hysteresis-loop, the dynamic stiffness and the mechanical damping.

While fracture mechanics investigations presuppose test specimens with cracks, hysteresis measurements can be made on specimens either with or without cracks, on which a material deformation can be measured by means of a wire strain gauge. Thus material changes can be measured in a pre-crack phase. Hysteresis measurements give an integral statement about the whole strain-test length. Therefore they assume largely homogeneous material behaviour. In contrast to acoustic emission measurements, with the hysteresis investigations material changes can be demonstrated which are connected with energy dissipation but not yet with noise emission as a consequence of a crack formation.

The material under investigation will be subjected to sinusoidal forced oscillations in a power-controlled servo-hydraulic test machine. The stress signal coming from the load cell of the pulsator and also the strain signal coming from an

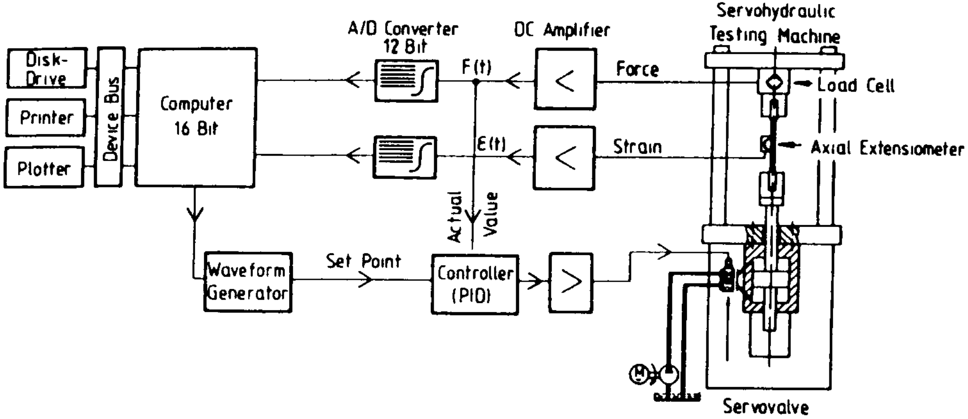


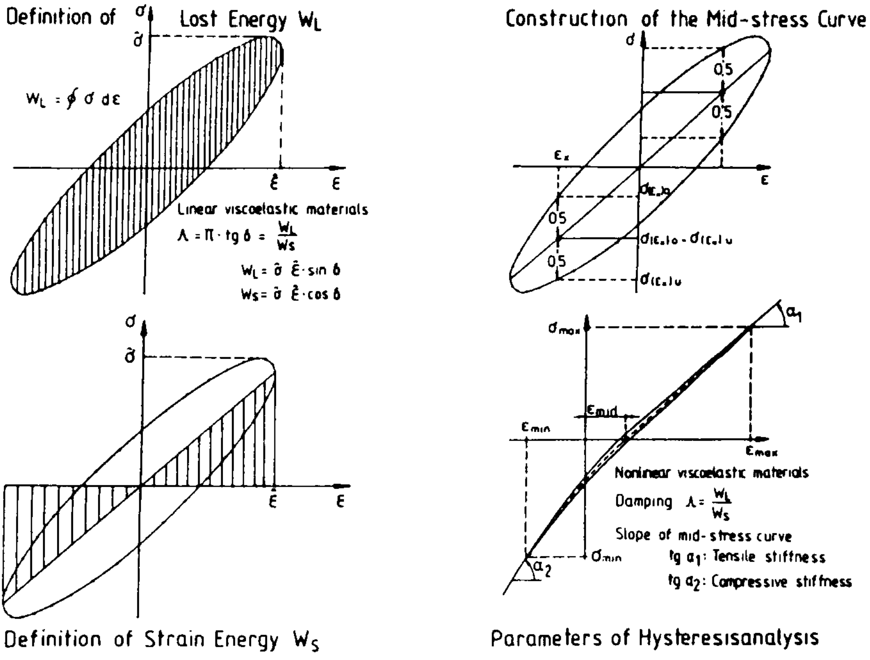
Figure 1. Configuration block diagram of hysteresis measurements.

axial extensiometer connected to the test specimen are measured simultaneously, amplified, digitalized and on-line processed on a computer (Figure 1). The computer controls the test machine and allows any possible load collectives to be produced and single hysteresis loops to be stored after a definite number of cycles. Every hysteresis-loop is stored in a mass memory in the form of 180 datapoints together with 27 calculated hysteresis characteristics. The evaluation software allows the test results to be documented either graphically or as a protocol.

For accurate measurement it is important that electronic phase shifts between stress and strain signal against the phase shift due to material damping be negligibly small.

Hysteresis Characteristics

The digitalized information is used to find out the strain, stiffness and energy-related characteristics. The characteristics differentiate between the material behavior in the tensile and compressive phase above and below, respectively, the medium stress. For the determination of the material damping, a mid-stress curve is fitted numerically to the hysteresis-loop, which is also used to determine the specimen's stiffness. The mid-stress curve always bisects the loop at the same strain value (Figure 2).



Definition of Lost Energy W_L

Construction of the Mid-stress Curve

Definition of Strain Energy W_S

Parameters of Hysteresisanalysis

Figure 2. Hysteresis analysis.

The slope of the mid-stress curve allows us to make a statement about the load-dependent stiffness of the material in different phases of the application of the load (i.e., tensile and compressive phase).

The change of the stiffness with the length of time of loading is a measure for the damage occurring during the fatigue load. In compounds, cracks as well as temperature increases and creep-occurrence cause module changes. As materials with cracks show a diminished stiffness under tensile load than under compressive load, one obtains valuable hints for the determination of the cause of damage by differentiating between tensile and compressive stiffness.

The mid-strain, determined by the intersection of the mid-curve with the strain-axes at the mid-stress, describes the cyclic creeping of the material, for example by crack formation or as consequence of a directed non-elastic deformation process.

Of the energy-related characteristics, the material damping reacts very sensitively as an integral damage measure to irreversible material changes, as well as to damage processes related to crack formation and crack growth, because the damping describes the transformation of energy during one cycle in a dimensionless form.

In the case of linear viscoelastic material behaviour the hysteresis-loop forms an ellipse. The material damping Λ is stress-independent and can be determined from the phase angle δ between the exciting sinusoidal force and the measured specimen deformation.

$$\Lambda = \pi \tan \delta \tag{1}$$

In order to determine the material damping also on non-linear viscoelastic material behaviour which can be observed on even very small mechanical tensions in SMC, the following procedure was chosen [6,7] (Figure 2):

1. The energy dissipated by the material in the form of viscoelastic deformation, crack formation, crack growth, and particularly by different friction and wear mechanisms corresponds to the area of the hysteresis-loop formed in one cycle. The area is determined by numerical integration and designated lost energy W_L.
2. The area between the calculated mid-curve and the abscissa from the strain minimum to the strain maximum is a measure for the stored energy in the material during one cycle. The area is determined by numerical integration and designated strain energy W_s. In the case of a mid-stress σ_m, the strain energy W_s is calculated between the mid-curve and the straight curve $\sigma = \sigma_m$.
3. The ratio between the volume-related figures lost energy and strain energy is designated material damping:

$$\Lambda = \frac{W_L \ (\mathrm{Nm/mm^3})}{W_s \ (\mathrm{Nm/mm^3})} \tag{2}$$

As shown in Figure 2, in the case of linear viscoelastic material behavior the equation $\Lambda = W_L/W_s = \pi \cdot \tan \delta$ is valid. The advantage of the definition of characteristics as shown here is that the characteristics are substituting continuously from linear to non-linear viscoelastic material behaviour.

Materials

By choosing a SMC-composition the aim can be, for example, to obtain a part with high geometrical accuracy, high surface quality, high optical quality and the possibility of easy staining. The optimal composition resulting from these demands may contradict the demand for favourable mechanical properties.

The complete microstructure of SMC is essentially influenced by the composition. The size, form and distribution of the glass fibre bundles, of the filler, the additives for shrinkage compensation, thickener and processing supports generate a strongly non-homogeneous material structure. Because of the cure shrinkage by warm hardening, unequally distributed cavities are produced—some of enormous size, depending on the kind of shrinkage compensation. The volume shrinkage of the resin in addition to different thermal coefficients of expansion of the various components, and also the strongly different interface strength, lead to a variety of micro-cracks and stress concentrations in the SMC even directly after production.

The object of this investigation is SMC with random orientation of the glass fibre bundles, and a matrix of UP-resin. The cutout roving bundles with the length of about 25 mm possesses soluble finish (Gevetex, Textil-GmbH, D-Herzogenrath, P 279); as a filler, uniformly non-surface processed Calcit (Millicarb, sizecut: 10 μm, OMYA GmbH, D-Köln); as thickener, MgO, were used; as initiator, tertiary Butyl-perbenzoate and as mould release, zinc stearate.

The following compositions were investigated:

Type 1: Influence of shrinkage compensation (Figure 7)
UP resin: terephthalic (®Palatal KR 51-22C, ϵ_b: 2.5–4%)
gf content: 30 wgt. %
resin to filler ratio: 1:1.5%
low shrinkage additive: no additive, thermoplastic additive, styrolic (®P14 HP), rubber additive (®Solpren 312, Philips Petroleum Comp., Oklahoma)

Type 2: Influence of resin toughness
UP resin: ortophthalic (®Palatal P14 ϵ_b: 1.8–2%)
terephthalic (®Palatal KR 51-22C, ϵ_b: 2.5–4%)
isophthalic (®Palatal KR 50-25, ϵ_b: 4%)
gf content: 30 wgt. %
resin to filler ratio: 1:1.5%
low shrinkage additive: no additive

Type 3: Influence of resin to filler ratio (Figure 12)
UP resin: terephthalic (®Palatal KR 51-22C, ϵ_b: 2.5–4%)
gf content: 30 wgt. %
resin to filler ratio: 1:0; 1:0.5, 1:1; 1:1.5; 1:2

Type 4: Influence of glass filler content (Figure 19)
UP resin: terephthalic

gf content: 10, 20, 30, 40 wgt. %
resin to filler ratio: 1 : 1
low shrinkage additive: no additive

The SMC-strand mats were cured on a laboratory press at 140°C and 74 bar for three minutes into plates of 350 × 400 × 4 mm^3. Out of these plates, type 3 specimens via DIN 53455 for tensile test were formed after röntgeno-graphic control and also flat specimens of 80 × 30 × 4 mm^3 for dynamic experiments. The free span in the dynamic tests was 40 mm.

EXPERIMENTAL PROCEDURE

In order to obtain a maximum of information about the dynamic behaviour of SMC's with different composition with a minimum sacrifice of time the following procedure has proven effective:

1. Quasi-static characterizations of the material in a tensile test
2. Dynamic characterization of the material in a "stepwise load increase experiment"
3. Single step tests for further dynamical investigations at single load levels in a range of 10^0 to 10^6 cycles
4. Accompanying light microscopical and SEM-experiments on crack surfaces and polished sections to characterize the damage progress

Cyclic "stepwise load increase experiments" accompanied by hysteresis measurements (Pt. 2) are especially well suited for characterization and differentiation of the influence of the composition on the expected damage behaviour. With load collectives, the manner and velocity of changes of the hysteresis characteristics are investigated far below, near, and above the damage area, depending on the position of the damage area ("Knee") in the tensile region. Before and after every load change the load is diminished to the quasi-damage-free starting level at 10 N/mm^2, in order to determine to what extent the material has been irreversibly damaged on the proceeding loads. Every three load collectives form a load cycle (Figure 4).

Generally tensile compressive alternating load experiments ($R = -1$) are used to investigate the relation of tensile and compressive load on the damage process. Preliminary experiments show that 10^4 cycles at a frequency of 10 Hz on each single load level correspond to an optimal time of stressing (ca. 20 min.). Below 10^3 cycles strong changes of characteristics can often be seen due to building-up processes. Above 10^4 LS no principal new knowledge could be obtained.

RESULTS AND DISCUSSION

Principal Dynamic Behaviour

Figure 3 shows as an example the changes in the hysteresis loop of a SMC (Type 3, 30% gf, Resin to filler = 1 : 1.5) in the "stepwise load increase experi-

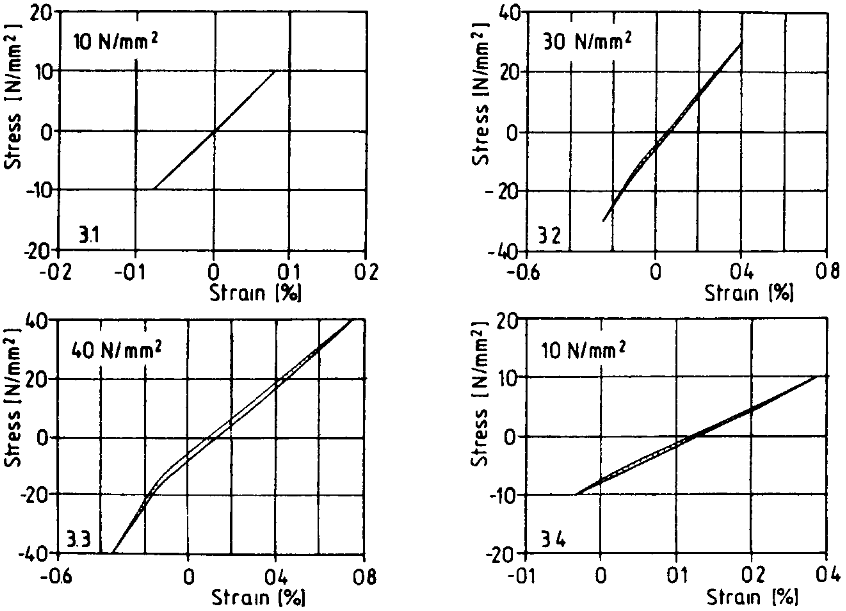


Figure 3. Change of hysteresis-loop for "stepwise load increase experiments."

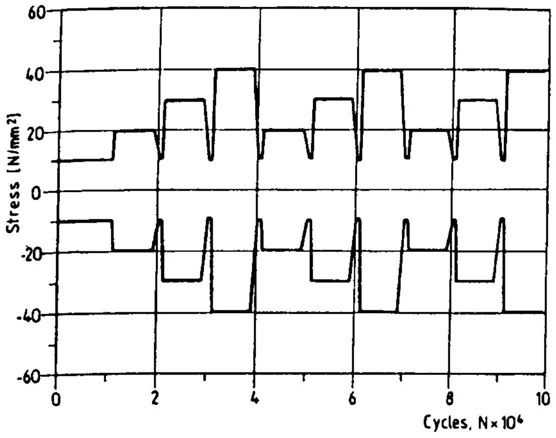


Figure 4. Load history for "stepwise load increase experiments."

ment." At alternating load tests ($R = -1$) of ±30 N/mm^2 the form of the hysteresis-loop deviates significantly from an ellipse describing only linear viscoelastic material behaviour (Figure 3.2). In the compressive region of the loop a "knee" is built up. With further increase of the load (Figure 3.3) the "knee" at about 12 N/mm^2 and also the related decrease of stiffness can be seen even more clearly. The position of the "knee" does not change with an increase in load. Related to the formation of the "knee," there is a clear shift of the hysteresis-loop in the tensile region. After unloading the material to the starting level of 10 N/mm^2 the strongly changed form and position of the hysteresis-loop (see Figure 3.1 and 3.4) indicates significant irreversible damage of the material due to the preceding load. It is very interesting that the damage of the material has no effect above a certain compressive load because the specimen regains nearly totally its original stiffness.

Static tensile-compressive tests of R-SMC for investigation of the formation of the "knee" show:

- The compressive strength is more than double the tensile strength.
- The exclusively compressive loading of the material produces no "knee" in the stress-strain diagram.
- A tensile load above a tension of about 35 N/mm^2 or a strain of about 0.2% leads to the well-known "knee" in the tensile region of the stress-strain diagram [8].
- As a result of damage of the material in the tensile region a "knee" is produced in the compressive region.

A strong micro-crack build-up in R-SMC is related to the "knee" in the tensile region under static and dynamic load. The formation and growth of micro-cracks is the reason for the process of stiffness, change of the hysteresis-loop in the "stepwise load increase experiment" shown in Figure 3. The shift of the hysteresis-loop in the tensile region is a hint that the cracks which form and develop in the tensile region cannot be totally closed after unloading. Crack build-up and growth lead to a diminished tensile stiffness. The "knee" in the compressive region can be explained by the fact that the cracks only close above certain compression so that the complete cross-section contributes to the stiffness. As the cracks at $\epsilon < 0$, i.e., $\sigma < 0$, close, unloading at a level of 10 N/mm^2 (Figure 3.4) produces a hysteresis-loop without "knee"—although with reduced stiffness.

The viscoelastic properties of the UP resin and also the increasing friction on crack surfaces related to crack formation and growth influence the damping behaviour as a function of the load and load-cycles.

From the behaviour of the material damping (Figure 5) in the "stepwise load increase experiment," it can be seen that even below a load of 20 N/mm^2 below the "knee," the first irreversible changes in the material behaviour are detectable with the highly sensitive measuring method in the tensile test. The load at the level of the "knee" (30 N/mm^2) is related to a significant damping increase evoked by the building and growth of microcracks. It should be noted that the material damping persists at a high level in a second load-cycle after unloading.

Figure 6 shows the behaviour of the material damping in the tension-compres-

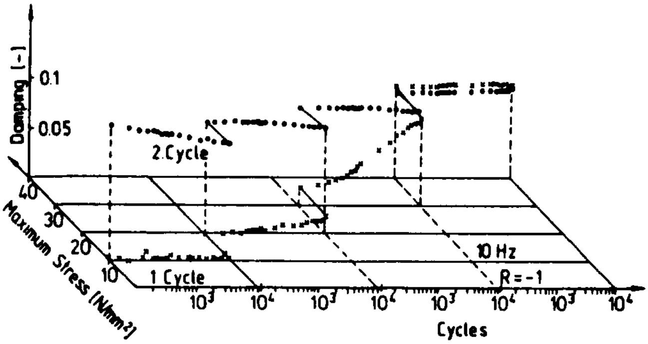


Figure 5. Damping for "stepwise load increase experiments."

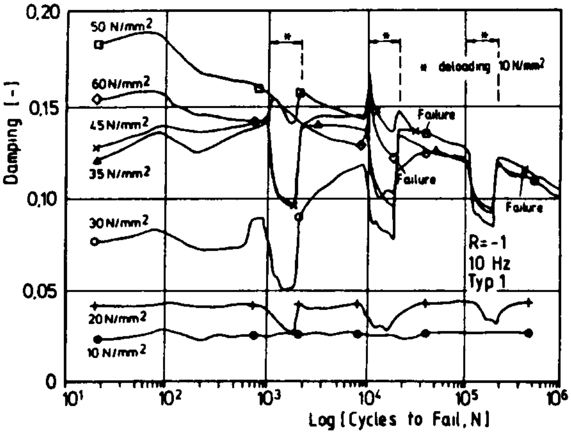


Figure 6. Damping of a R-SMC without additives (type 1).

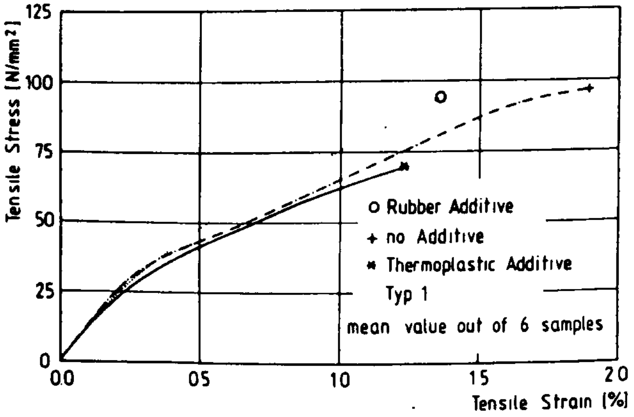


Figure 7. Influence of low shrink additive (type 1).

sion alternating region of different load levels on a non-shrinkage-compensated SMC. After 10^3, 10^4, 10^5 cycles at the indicated load-levels the specimens are unloaded to the basic level of 10 N/mm^2 for 10^2, 10^3 and 10^4 cycles, respectively. The specimens are tested for 10^6 cycles or to the breakpoint.

Depending on the load it is possible to distinguish between the following three graphs:

1. The damping increases only slightly with the number of cycles but can still be detected with our sensitive measuring method (10, 20 N/mm^2).
2. The damping increases significantly with the number of cycles and shows a maximum after about 10^4 cycles (30, 35 and 40 N/mm^2).
3. The damping decreases with the number of cycles after a short increase at the beginning (50, 60 N/mm^2).

An essential observation is that a fracture on these compositions (Type 3, 30% gf, resin to filler = 1 : 1.5) does occur in a phase with decreasing damping. Here it is particularly apparent that after 10^4 cycles all damping graphs of the curve-types 2 and 3 show the same behaviour, independent of the load-level.

Influence of Low Shrinkage Additive

The effect of low shrinkage additives to the SMC is discussed for example in [9,10]. The stress-strain diagram (Figure 7) shows that the material of type 1 (30% gf resin to filler = 1 : 1.5) without shrinkage compensation shows the same solidity, but significantly higher elongation at break, as the same material with rubber modifier. Because of its diminished accuracy of size it technically has only minor significance. The thermoplastic modified SMC possesses in contrast only low tensile strength and elongation at break. All three types of SMC show a "knee" of at least 30 N/mm^2.

Microscopic investigations of polished sections show a relation between deformation behaviour and the homogeneity of the micrograph. The thermoplastic-modified material contains big irregular cavities of up to 1 mm in diameter. The other two materials show a uniform structure with equally distributed voids. The rubber-modified material also shows the equally distributed rubber particles in the micrograph.

The principal conclusions from the static tensile-test can be found again in the dynamic tests. Figure 8 shows the tensile stiffness in the "stepwise load increase experiment" in accordance with the load history of Figure 4. The SMC with thermoplastic low shrinkage additive has, from the beginning of the loading, the least stiffness, which can be explained by the higher amount of voids as a result of the processing. The distinct decrease in stiffness of the three materials reaching the load level of 30 N/mm^2 is explainable by the same position of the "knee" in the tensile test that also starts at 30 N/mm^2 (Figure 7).

The influence of the rubber modifier in contrast to the non-modified SMC can more exactly be determined by the damping behaviour in the single step test (Figures 6 and 9). The damping level at loadings below the "knee" (<30 N/mm^2) is on the whole higher than in the non-modified SMC. Also at low stresses, a distinct increase in damping is determinable. In the same case a union of the damp-

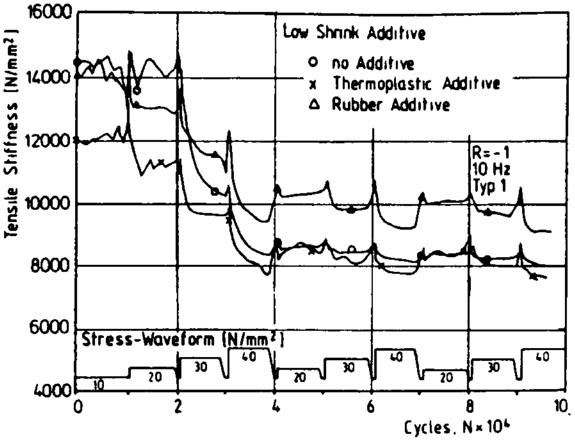


Figure 8. Influence of low shrink additive (type 1).

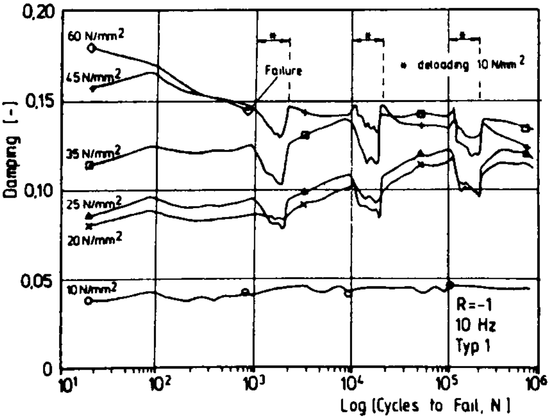


Figure 9. Damping of rubber modifed R-SMC (type 1).

ing curves at higher cycles results. While the non-modified SMC at loadings up to 20 N/mm^2 shows practically no change in the damping level, this is valid for the low shrinkage modified SMC only for stresses ≤ 10 N/mm^2. An important fact is that dynamic damage of SMC can be detected already by loading below the "knee" in the tensile test.

Influence of Resin Toughness

The tensile test of SMC with different resin toughness (Type 2, 30% gf; resin to filler = 1 : 1.5) shows that a higher resin toughness clearly improves the deformation behaviour. In the "stepwise load increase experiment" the influence of the resin toughness on the damping (Figure 10) and the stiffness in the tensile region (Figure 11) is still insignificant. All three materials show at a stress level of 30 N/mm^2 a significant increase on reaching the statically measured "knee" in the damping, connected with a decrease in stiffness to nearly half of the starting level. Comprehensive investigations of the influence of the resin toughness are not yet completed.

Influence of Resin to Filler Ratio

The most significant influence on the dynamic fatigue behaviour of R-SMC is exerted by the variation of the resin to filler ratio with constant glass fibre content (Type 3, 30% gf).

Already in the tensile test, the dependence of the "knee" in the stress-strain diagram to the filler content is distinctly recognizable (Figure 12). The material without filler has a slightly decreasing stress-strain curve without forming a "knee." The material with resin to filler ratio = 1 : 0.5 has a higher stiffness at less loading, but at higher loadings a stronger decreasing curve. Only a resin-to-filler ratio of about 1 : 1 and higher produces a "knee" at 40 N/mm^2.

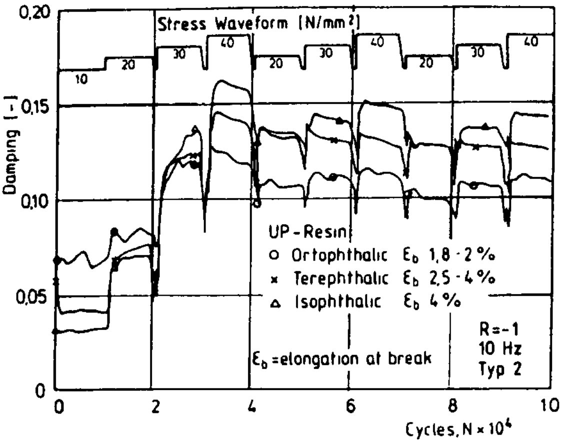


Figure 10. *Influence of resin toughness on damping (type 2).*

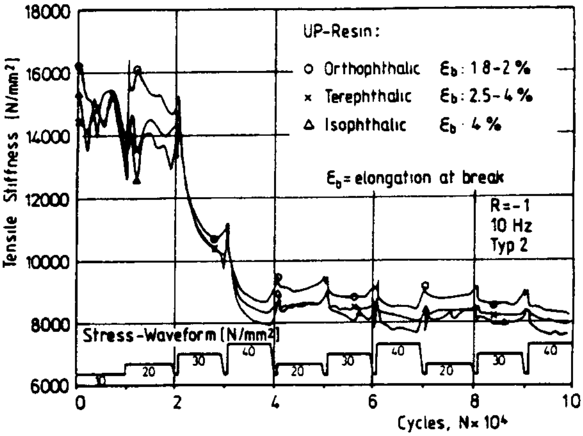


Figure 11. Influence of resin toughness (type 2).

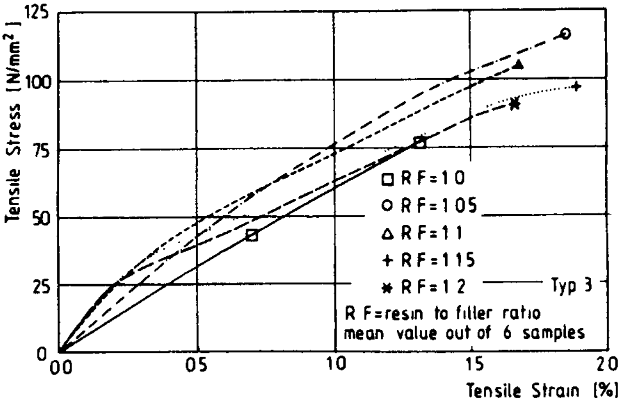


Figure 12. Influence of resin to filler ratio (type 3).

A resin-to-filler ratio of 1 : 2 yields a sharp "knee" above about 30 N/mm^2. The formation of the "knee" and the decrease of module above the "knee" connected with it becomes more distinct the larger the filler content is. The material with resin-to-filler ratio of 1 : 0.5 has the highest ultimate strength and, above a tensile stress of about 30 N/mm^2, the greatest stiffness.

With the aid of hysteresis measurements one can determine, on the basis of the form of the hysteresis-loop, that the stiffness behaviour in the compressive region of the loading is also dependent on the resin-to-filler ratio. With increasing filler content the "knee" in the compressive region gets more significant. The location of the "knee" at a compressive tension of about 20 N/mm^2 is scarcely influenced by the resin-to-filler ratio and the tension amplitude (Figure 13).

Obviously the boundary surface between the resin and the filler particles is a damage criterion which determines the production of micro-cracks in R-SMC. As the mineral-filler particles made of Calcit are not supplied with a finish, they only have diminished adhesion at the resin. In addition the rhomboedric form of the single particles produces notch tensions which are favourable for the micro-crack formation.

As the stiffness behaviour in the "stepwise increase of load experiment" (Figures 14 and 15) shows, a significant increase in stiffness in the tensile and in the compressive phase of the alternating loading can be obtained with the low-priced filler below an amplitude of 20 N/mm^2. At a load amplitude of 30 N/mm^2 the increase in stiffness due to the filler is lost. In the tensile region the stiffness decreases with the number of cycles down to the level of a material without filler, especially at high filler content. The stiffness will then be determined only by the glass fibres. In the compressive region the cracks are closed, and thus the material stiffness is largely maintained.

Of course the loosening in the whole compound due to increasing micro-crack production in the tensile region yields a decrease in stiffness in the compressive

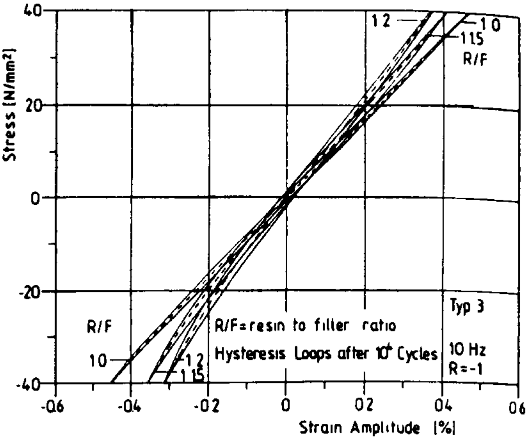


Figure 13. *Change in hysteresis-loop for various resin to filler ratios.*

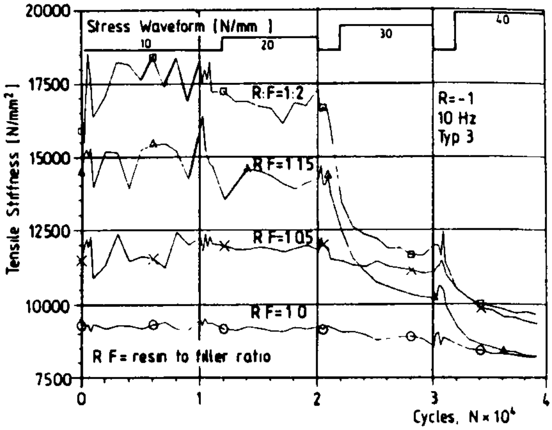


Figure 14. Influence of resin to filler ratio (type 3).

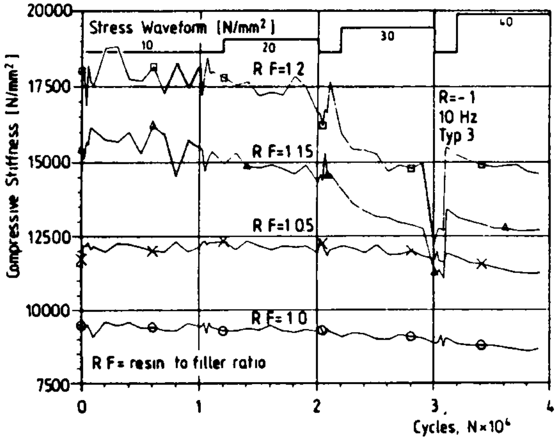


Figure 15. Influence of resin to filler ratio (type 3).

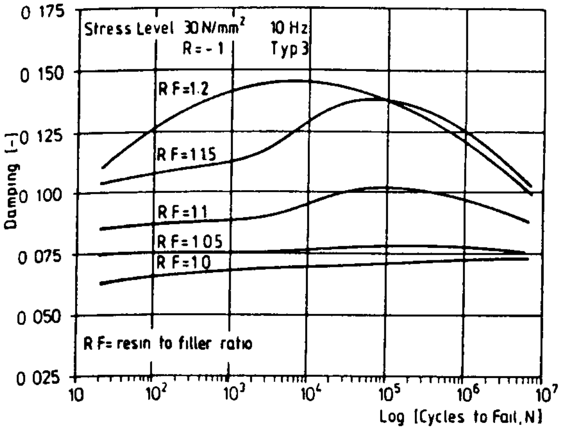


Figure 16. *Influence of resin to filler ratio at 30 N/mm^2 stress level.*

region. The damage progress depending on the filler content can be clearly followed on the basis of the changes in material damping. Figure 16 shows the damping behaviour in a single step test at a load level (σ = 30 N/mm^2) at which a "knee" forms in the tensile test on materials with higher filler content. Because of increasing interface with increasing filler content, the damping grows. The higher the filler content the more significant the increase in damping.

With increasing filler content the shape of cracks being visible through the microscope gets more irregular. The crack density goes up, due to increasing points of weakness (resin filler surfaces), at the same number of cycles. The steeper increase of damping with increasing filler content is explainable, first, by the higher energy loss caused by irregularly shaped crack boundaries, and secondly, the generally larger crack area at a constant number of cycles.

The decrease in damping with increasing cycles of SMC with high filler content shows that with progressing fatigue the energy being dissipated by crack friction becomes continually less. The microscopic examination shows that in this phase of fatigue new friction surfaces due to micro-crack formation become fewer. From SEM-examinations of the crack boundaries it can be supposed that more and more smaller particles get into the crack areas in the tensile load phase and jam the cracks, thereby clearly reducing the effective friction area between the crack boundaries. This is supported by the observation that despite the decrease of damping the mid-strain rises with increasing filler content, i.e., many small filler particles (Figure 17).

With a load amplitude of 30 N/mm^2 no failure was detected up to 10^7 cycles in any R-SMC under investigation. At higher load levels a failure occurs, whereby the damping progress is determined by the filler content. On SMC with a resin-to-filler ratio = 1:0 resp. 1:0.5 the lost energy and the damping (Figure 18, σ = 50 N/mm^2) increases.

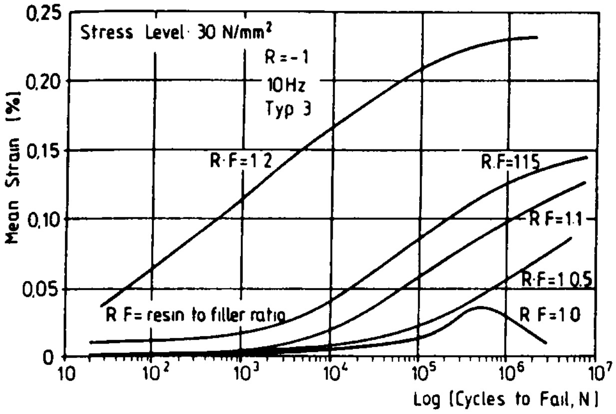


Figure 17. Influence of resin to filler ratio at 50 N/mm² stress level.

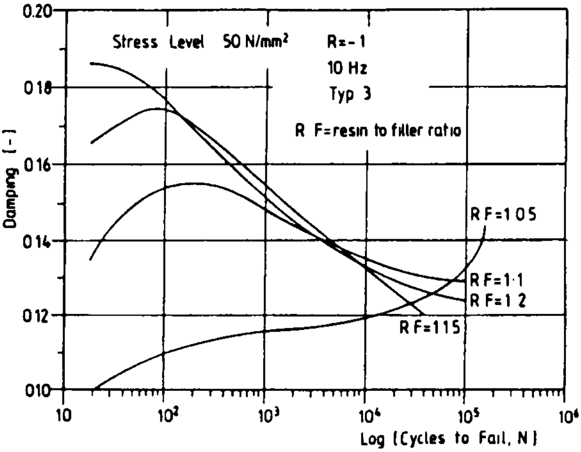


Figure 18. Influence of resin to filler ratio at 50 N/mm² stress level.

Simultaneously the crack density increases monotonously till failure. As previously discussed, these materials show no distinct "knee" in the tensile test. On SMC with a distinct "knee" in the tensile test, i.e., with high filler contents and above 10^3 cycles, only a decreasing of damping, and, simultaneously, a small decrease of energy loss are observable, despite an increasing crack density. A failure is accompanied by micro-crack formation in the load direction, in addition to the already existing micro-cracks perpendicular to the load direction. In this manner whole parts of the specimen are uncoupled from the loading.

Additional interface debonding occurs at the fibre bundles, so that the specimens fail by pull-out of the fibre bundles independent of the filler content.

Influence of Glass Fibre Content

With increasing glass fibre content at a constant resin-to-filler ratio the influence of the filler becomes less (Type 4, resin-to-filler ratio 1 : 1). Furthermore the "knee" in the tensile test becomes less distinct and moves to higher loadings with increasing glass fibre content. Stiffness, strengh and to a small extent the breaking elongation increase (Figure 19).

An increase of the filler content at constant glass fibre content improves the stiffness behaviour of R-SMC only at load levels below the "knee." With a constant resin-to-filler ratio, an increase of the glass content improves the fatigue behaviour distinctly at all load levels because of the rise of the "knee." Figure 20 shows with the progress of tensile stiffness at a load level of 30 N/mm², that with increasing glass fibre content the module as a whole rises, of course, but also that the decrease of the module slows down with the number of cycles. Parallel to the change in stiffness the progress of the damping characterizes the progress of the material damage as a function of load cycle. As already discussed, the maxima in the damping process become less distinct with increasing glass fibre content (Figure 21).

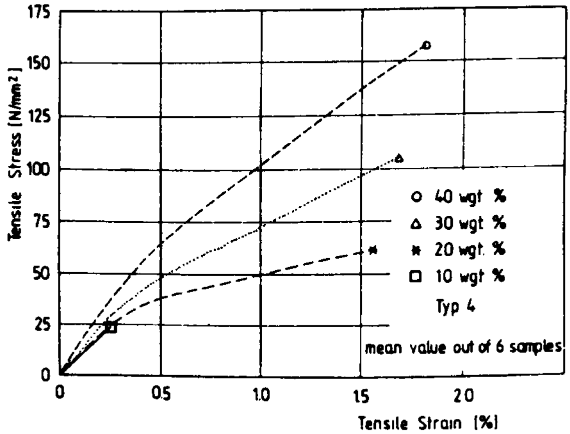


Figure 19. Influence of glass fibre content (type 4).

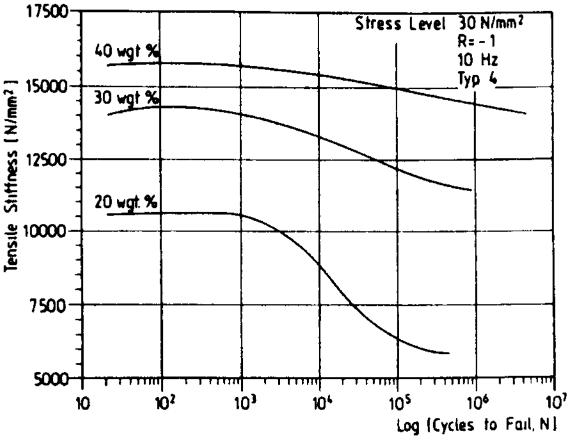


Figure 20. *Influence of glass fibre content at 30 N/mm² stress level.*

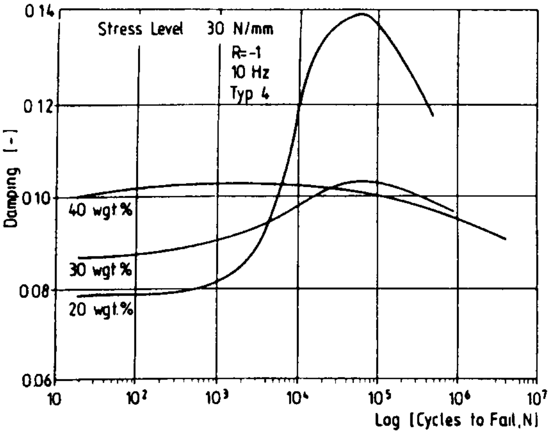


Figure 21. *Influence of glass fibre content at 30 N/mm² stress level.*

SUMMARY

From the hysteresis measurements on SMC the following conclusions can be reached:

- The measuring method makes it possible to determine damage phenomena before a specimen failure in the stage preceding the beginning of macroscopical cracks. For technical applications the change in stiffness behaviour under dynamic loading is of special interest. The material fatigue can be still more sensitively described by damping measurements.
- Statements can be made about the damage progress, so that it is possible to make specifications of approved load levels.
- As SMC shows a high decrease of stiffness under dynamic loading, for the engineering valuation of the fatigue behaviour not the cycles to failure, but the change in stiffness, should be referred to.
- The high sensitivity of the measurement method makes it possible to evaluate quickly the influence of various composition components and consequently to improve the material.
- Besides the parameter "material damping," an integral damage criterion, the constructionally important dynamic module of elasticity in the tension and compressive region, and the mid-strain, which describes the creep-properties of a material under dynamical loading, are specially suitable to characterize fatigue behaviour.

ACKNOWLEDGEMENTS

The research project was financially supported by the German Federal Department for Research and Technology and Daimler Benz AG, Stuttgart (West Germany), and conducted by Daimler-Benz AG together with the "Institut für Werkstofftechnik" at the University of Kassel, Kassel (West Germany).

The authors are indebted to Mr. Ing. Lawonn, BASF AG, Ludwigshafen (West Germany) and Mr. Ing. Liebold, Fibron Mellert AG, Bretten (West Germany) for valuable hints and for supplying the SMC samples.

This paper was presented at the 41st Annual Conference, Reinforced Plastics/Composites Institute, The Society of the Plastics Industry, Inc., 1986.

REFERENCES

1. Knauer, B. and Th. Knupfer. "Schwingverhalten von Mischverbunden unter besonderer Berücksichtigung von Kriechvorgängen und Schädigungsprozessen," *Verstarkte Plaste*. Berlin:DDR (1984).
2. Das, B. and H. S. Loveless. "Effects of Structural Resins and Chopped Fiber Lengths on the Mechanical and Surface Properties of SMC Composites," *SPI Prepr.*, Annual Conf. Reinf. Plast. Comp. Inst. (Feb., 1981).
3. Gracewski, A. S., J. F. Mandell and F. J. McGarry. "Factors Affecting the Impact Resistance of SMC Materials," *Proc. Ann. Conf. Reinf. Plast. Comp. Inst.*, S. 23D, 14, 4S, 1T, 1Q (1979).
4. Jeffery, M. R., J. A. Sourour and J. M. Schultz. "Fatigue Behavior of Thermosetting-Polyester Matrix Sheet Molding Compounds," *Polymer Composites*, 3(1) (Jan., 1982).

5. Mandell, J. F. "Matrix Cracking in Short Fiber Reinforced Composites under Static and Fatigue Loading," Composite Materials: Testing and Design (Sixth Conference), ASTM (1982).
6. Lazan, B. J. *Damping of Materials and Mambers in Structural Mechanics*. Oxford:Pergamon Press (1968).
7. Renz, R. "Zum zügigen und zyklischen Verformungsverhalten polymerer Hartschaumstoffe," Dissertation, Universität Karlsruhe (1977).
8. Puck, A. "Zum Deformationsverhalten und Bruchmechanismus von unidirektionalem und orthogonalem Glasfaser/Kunststoff," *Kunststoffe, Bd*. 55, Heft 12, S. 913 ff (1965).
9. Lee, B. L. and F. H. Howard. "Effect of Matrix Toughening on the Crack Resistance of SMC under Static Loading," 38th Ann. Conf., Reinforced Plastics/Composite Institute, SPI, Febr. 711, Houston (1983).
10. South, Jr. A. "A Unique Rubbermodifier for SMC," SPE, National Techn. Conf.; 6-8.11, Detroit (1979).