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Flexural Fatigue Testing of Polyesters

E. HAGERUP, *California Research Corporation, Richmond, California*

INTRODUCTION

Flexural fatigue properties under known excited cyclic stress are fairly well established for present-day glass-reinforced polyesters, as illustrated in Figure 1. In view of the differences in composition and inherent properties of the resins, the spread in laminate strength is surprisingly narrow.

One aspect of fatigue that has received relatively little attention is the effect of cyclic forces at resonance. In structures operated at increasingly higher speeds and frequencies, such as aircraft, resonance fatigue is rapidly becoming a major problem. Figure 2 shows the resonance curve for a simple linear system having a single degree of freedom and excited by a force of constant magnitude but variable frequency. As the frequency increases, the amplitude increases to a maximum at the point of resonance, where the frequency of the exciting force equals the natural frequency of the vibrating system.

Severity of a resonance vibration may be specified in terms of a resonance amplification factor. This is defined as the ratio between amplitudes, at resonance and at rest, induced by the same exciting force. The stress at resonance is correspondingly amplified and can, in cases of low damping, result in unexpected and very premature failure. The advantage of high damping in resonance fatigue is demonstrated also in Figure 3. Here, a laminate with low endurance limit but high damping far outlasts the stronger low-damping aluminum.

Glass-reinforced resin laminates are heterogeneous systems with resultant properties derived from the resin, the glass, and from their mutual interaction. The present paper describes testing of fatigue properties of the resin itself and of the resin containing two plies of glass cloth in positions corresponding to the outermost plies in a laminate.

EXPERIMENTAL PROCEDURE

The resins were made from unsaturated polyesters modified by isophthalic acid, prepared by a two-step method[1] and crosslinked with styrene. Table I shows composition and curing characteristics of the resins. Gel times, time to peak exotherm, and peak exotherm were determined on a 50 g. sample in a 150 ml. beaker in air at room temperature.

Castings $^1/_2$ in. thick were made in a 5.5 in. by 5.5 in. mold consisting of a stainless-steel frame clamped between glass plates. Glass reinforcement

TABLE I. Composition of Isophthalic-Modified Polyesters

	Isophthalic acid per maleic anhydride (fumaric acid)										
	3:1		1:1					3:4	2:3	1:2	2:1
	A	B	C_1	C_2	C_3	C_4	D	E	F	G	H
Composition (mole ratio)											
Isophthalic acid	3	3	1	1	1	1	1	3	2	1	2
Adipic acid	—	—	—	—	—	—	—	—	—	—	1
Maleic anhydride	1	1	1	1	1	1	1	—	—	—	1
Fumaric acid	—	—	—	—	—	—	—	4	3	2	—
Ethylene glycol	—	—	—	—	—	—	—	3.68	1.75	1.1	—
Propylene glycol	4.4	—	2.1	2.1	2.1	2.1	—	—	—	—	—
Diethylene glycol	—	4.2	—	—	—	—	2.1	—	—	—	4.2
Triethylene glycol	—	—	—	—	—	—	—	3.68	3.5	2.2	—
Least-chain length[a]	355	512	370	370	370	370	524	529	581	583	549
Least-chain length per moles maleic and fumaric in least chain[a]	29.8	42.0	15.2	15.2	15.2	15.2	21.5	19.0	19.9	17.6	45.0
Polyester, wt.-%	50	50	50	55	60	60	50	50	50	50	50
Styrene, wt.-%	50	50	50	45	40	40	50	50	50	50	50
Catalyst combination											
Inhibitor, wt.-%											
Tertiary butyl catechol[b]	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0	0
Accelerator, wt.-%											
Cobalt[c]	0.018	0.005	0.009	0.018	0.009	0.009	0.009	0.027	0.023	0.027	0.005
Catalyst, wt.-%											
Methyl ethyl ketone peroxide[d]	0.6	0.6	0.3	0.3	0.3	0.225	0.225	0.225	0.45	0.225	0.6
Benzoyl peroxide[e]	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Gel time, hrs.[f]	$^3/_4$	$^3/_4$	$1^1/_4$	$1^1/_2$	$1^1/_4$	$2^1/_4$	$1^1/_2$	$3^1/_2$	$2^1/_4$	$1^1/_2$	$^3/_4$
Time to peak exotherm, hrs.	$2^1/_4$	$1^3/_4$	2	2	$1^3/_4$	$3^1/_4$	2	$4^1/_2$	$3^1/_2$	$2^1/_2$	$1^1/_4$
Peak exotherm, °C.	35	92	150	144	140	105	143	120	107	130	108
Shrinkage after final oven cure for 1 hr. at 150°C.	5.1	5.9	5.1	4.2	4.0	3.9	6.4	6.9	7.5	7.1	5.9

[a] Cf. Figure 15. [b] Added as a 5% solution in xylene. [c] Added as a cobalt naphthenate solution in petroleum thinner (6% cobalt). [d] Added as a 60% solution in dimethyl phthalate (Lupersol DDM). [e] Added as a 50% paste in tricresyl phosphate (Luperco ATC). [f] Determined at 24°C. ambient temperature (50 g. sample in 150 ml. beaker to make disk 2 in. in diameter and 0.8 in. thick).

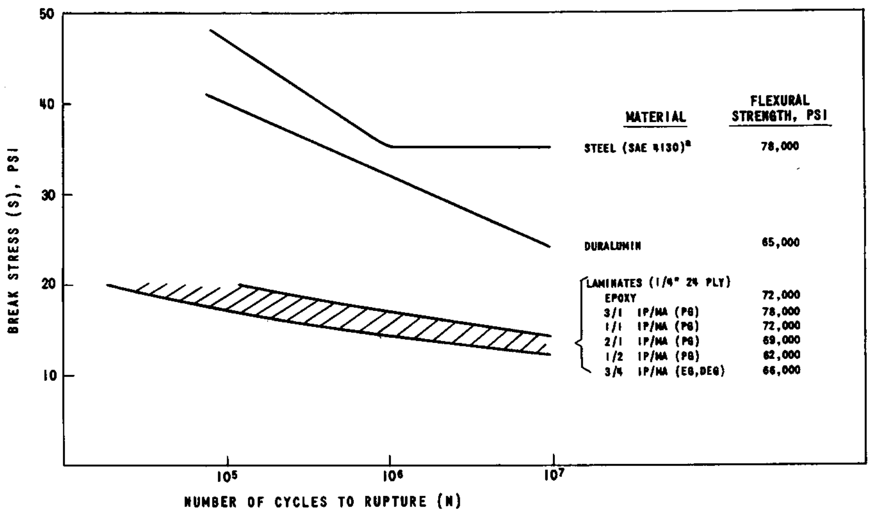


Fig. 1. Fatigue strength of structural materials. Data on steel and Duralumin, courtesy N. Fried, *SPI Conf. Preprint, Sect. 5-A*, 1957. Data on laminates from unpublished data.

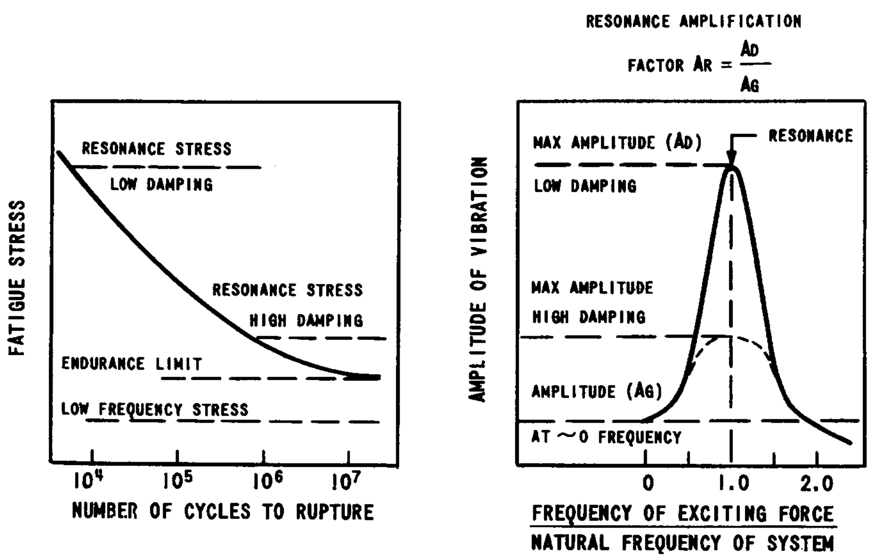


Fig. 2. Effect of damping in resonant vibration.

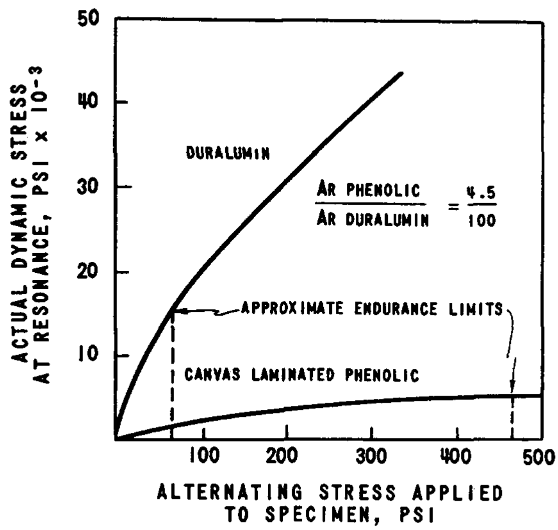


Fig. 3. Resonance fatigue of Duralumin and a laminated phenolic. Courtesy B. T. Lazan, *SPI Conf. Preprint, Sect. 1-A,* 1956.

was incorporated as two plies of glass fabric in positions corresponding to the outermost plies in a laminate. An 0.03 in. thick frame of polyethylene terephthalate film next to the glass plates separated the fabric from the mold walls. The Volan-finished fabric was plain woven with untwisted yarn in both warp and filling. The castings were deaerated in a vacuum desiccator before gelling.

Ten bars $^1/_2$ in. wide such as shown in Figure 4 were cut from each casting 16–18 hrs. after molding.

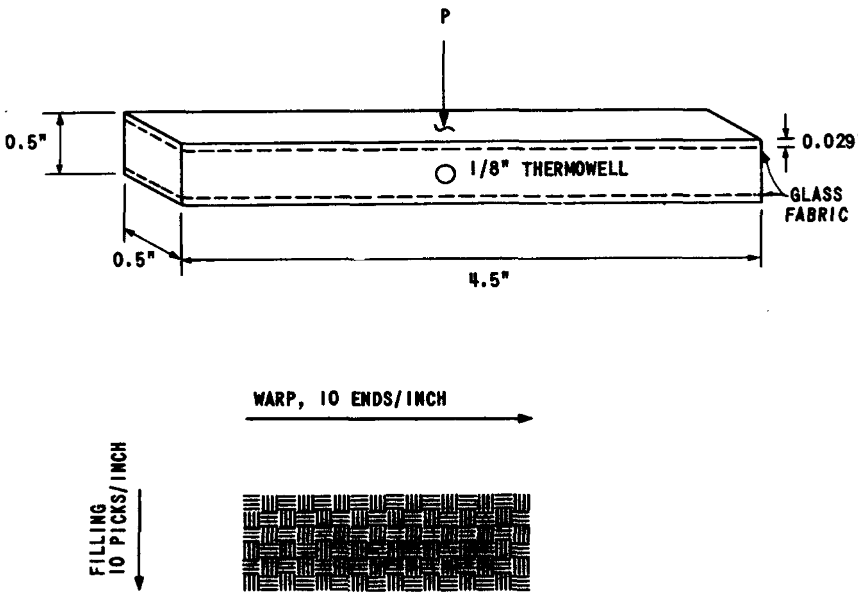
A Sonntag Fatigue Testing Machine, Model SF-1-U,[2] was used for measuring dynamic properties and fatigue strength in reversed bending by the Prot method, as described in Figures 5 and 6. To evaluate damping, the temperature rise during testing was measured by inserting a thermocouple in the neutral plane of the test bar. This could be done without affecting the mechanical parameters except in cases in which extreme brittleness caused excessive serration during drilling of the thermowell.

DISCUSSION

Figures 7–9 demonstrate the major differences in dynamic behavior between a typical rigid polyester with brittle fracture and a so-called high-impact polyester with plastic fracture.

A brittle fracture implies that the bar does not yield before breaking which, in terms of the test, means that the relationship between stress and deflection remains independent of time all the way to fracture. In plastic fracture, on the other hand, the bar starts to yield at a stress called the yield stress, beyond which the deflection is not only stress-dependent but also time-dependent. The close proximity of yield points and endurance limits for plastic resins confirms the validity of Prot's method for extrapolating the latter parameter.

Reproducibility of the results is directly related to the type of fracture, ranging from poor for brittle to very good for plastic fractures. Inability of the brittle resin to dissipate local stress concentrations is also indicated



TREVARNO GLASS FABRIC
EX: COAST MANUFACTURING AND SUPPLY CO.
LIVERMORE, CALIFORNIA

DESIGNATION: KA·980 (317 G/M²)
FINISH: VOLAN AC/FI6M
YARN: UNTWISTED, 3570/1180 DENIER
MONOFILAMENT: 3.03 DENIER

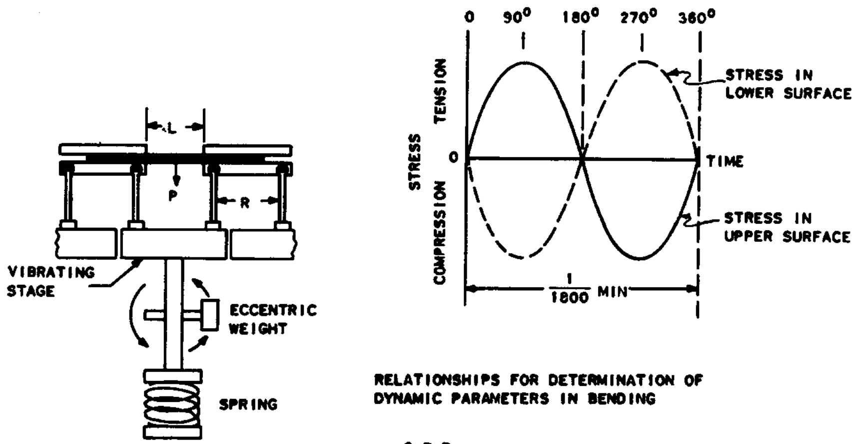
CROSS SECTIONAL RATIO GLASS/RESIN:
1.64 MM²/162 MM², (1% GLASS)

Fig. 4. Test bar as used with two layers of reinforcing glass cloth.

by the fractures occurring at, or anywhere between, the jaws, whereas the plastic resin invariably breaks in the middle, where the exciting stress is highest.

Incorporation of two layers of glass cloth in positions corresponding to the outermost plies in a laminate shows that both plastic and brittle resins give stiffer composites. However, only the plastic resin realizes its inherent break deflection to give correspondingly higher strength. Failure of the brittle composite to reach the break amplitude of the resin itself indicates that the breakdown in this case occurs at the interface. With glass present, failure is preceded by progressive opaqueness of the glass–resin interface starting at the warp–filling crossovers. These points, therefore, probably act as very potent stress raisers to induce delamination and, in the case of a brittle resin, premature failure.

Additional plies of glass cloth are expected to increase composite stiffness further. Flex failure will, however, in all cases take place near the outermost plies where the stresses are highest. Break deflections of the present two-ply laminates should, therefore, remain the same, providing that the inherent resin properties remain unchanged at the higher glass loadings.



RELATIONSHIPS FOR DETERMINATION OF DYNAMIC PARAMETERS IN BENDING

$$S = \frac{3RP}{bh^2} \quad (1)$$

$$E = \frac{RLS}{yh} \quad (2)$$

S - MAX. BENDING STRESS AMPLITUDE, PSI
R - LEVERAGE (3 INCHES)
P - PEAK FORCE, LB
b - SPECIMEN WIDTH, INCHES
h - SPECIMEN THICKNESS, INCHES
E - DYNAMIC ELASTIC MODULUS, PSI
L - DISTANCE BETWEEN GRIPS (2 INCHES)
y - MAX. BENDING AMPLITUDE, INCHES

Fig. 5. Arrangement for flexural fatigue testing.

Figures 10–12 show the effects on dynamic flex behavior of a rigid polyester produced by variations in rate and degree of cure and styrene content.

Rate of cure as visualized by the peak exotherm appears to have the greatest single effect on all the dynamic properties. Cured at peak exotherms of 140–150°C., castings containing 40–50% styrene are all brittle after 24 hrs. at ambient temperature with no further time effect. Reduction of the peak exotherm to 105°C. produces a casting with plastic fracture which becomes progressively stronger with time at ambient temperature. Final oven cure turns this casting brittle also, but with a gain in fatigue strength of some 40% over the faster cured specimen.

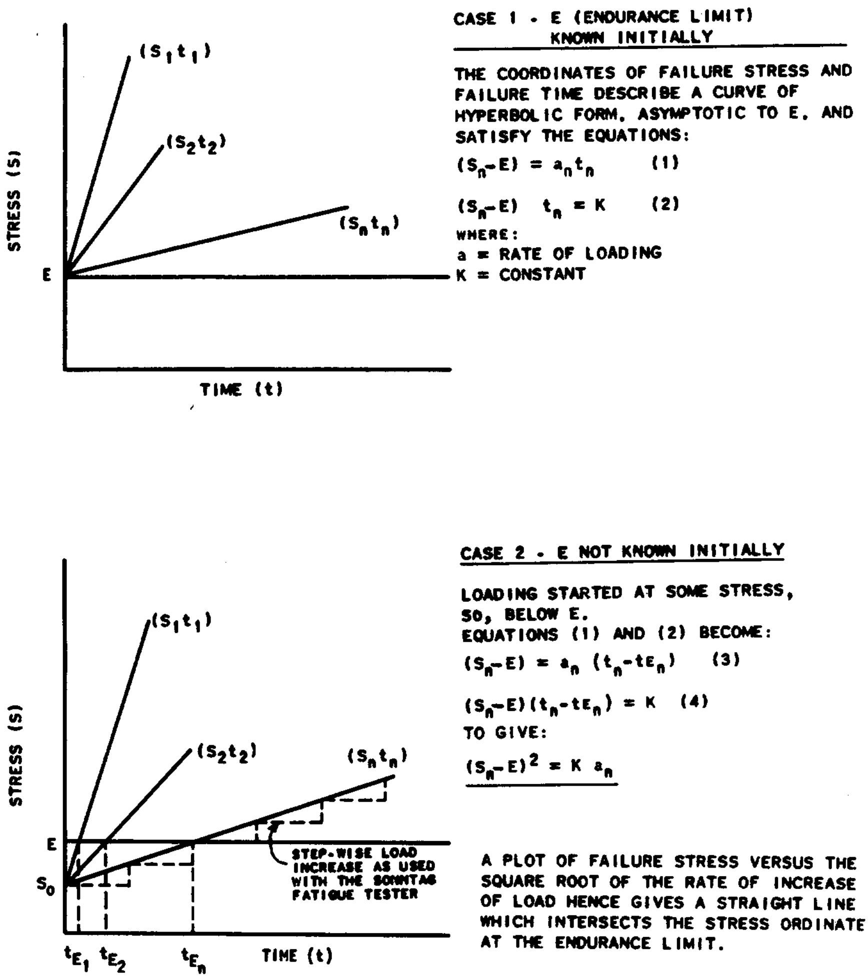
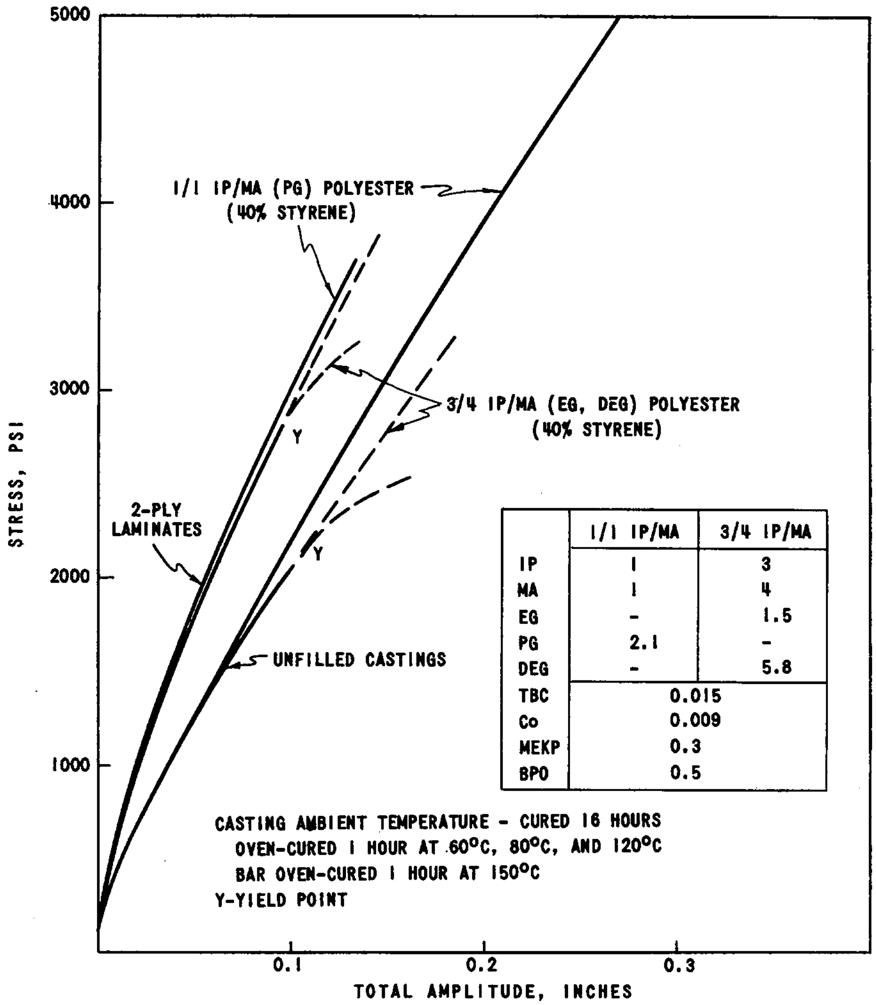


Fig. 6. Derivation of the Prot method. Courtesy of L. S. Lazar, *SPI Conf. Preprint, Sect. 5-E*, 1957.

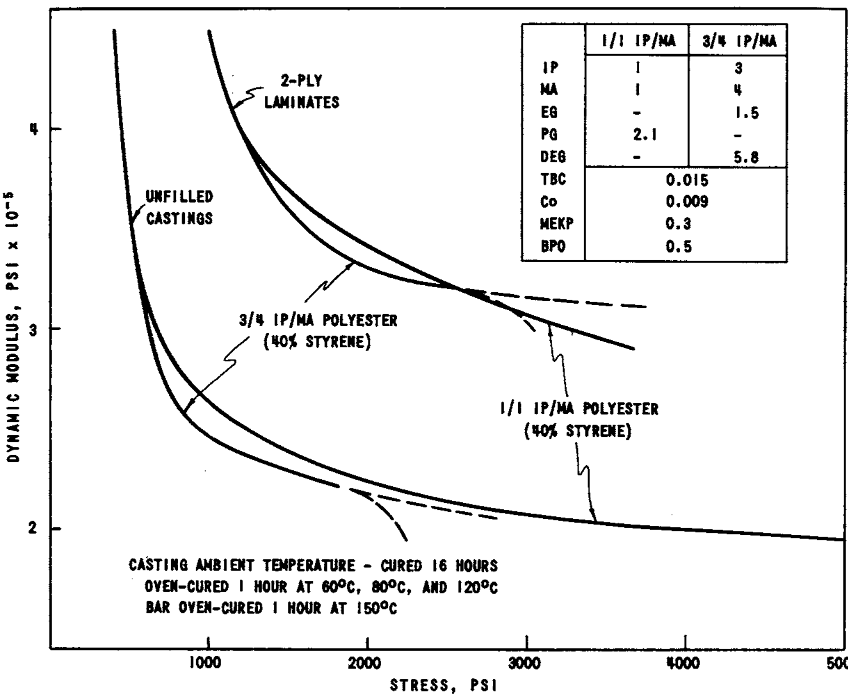


	1/1 IP/MA	3/4 IP/MA
IP	1	3
MA	1	4
EG	-	1.5
PG	2.1	-
DEG	-	5.8
TBC	0.015	
Co	0.009	
MEKP	0.3	
BPO	0.5	

Fig. 7. Stress versus deflection of polyesters in reversed bending.

Bars which yield before break have high damping capacities in terms of the temperature rise at break. Differentials as high as 35°F. were measured for the casting cured at a peak exotherm of 105°C., as compared with 2–5°F. for the brittle castings.

Figures 13 and 14 show dynamic properties of several polyesters in the 3:1 to 1:2 isophthalic acid/maleic anhydride range with the use of several different glycols. The spread in properties caused by changes in the polyester composition is quite large, both in the ambient-cured condition as well as after final oven cure. In their well-cured state, three different

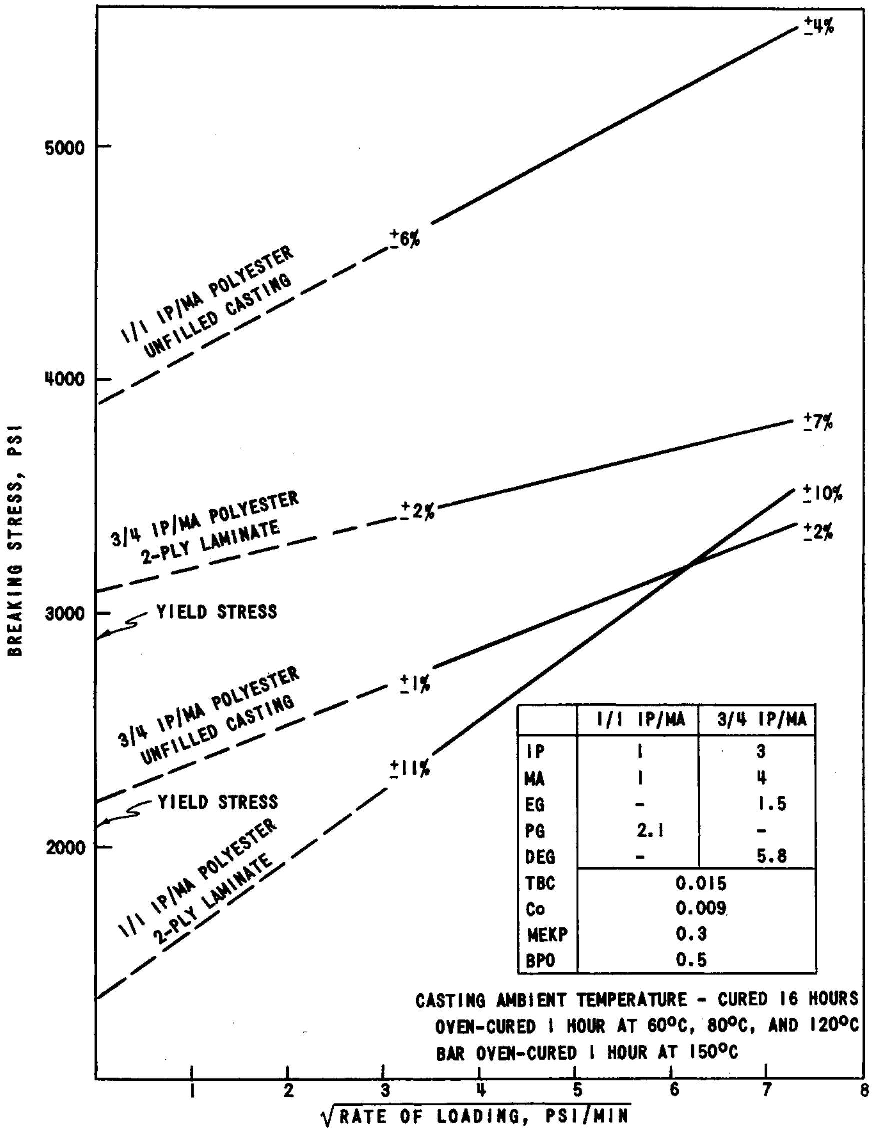


	1/1 IP/MA	3/4 IP/MA
IP	1	3
MA	1	4
EG	-	1.5
PG	2.1	-
DEG	-	5.8
TBC	0.015	
Co	0.009	
MEKP	0.3	
BPO	0.5	

Fig. 8. Dynamic modulus versus stress for polyesters in reversed bending.

types of glass/resin systems could be distinguished: (*1*) weak and high damping, plastic (B); (*2*) strong and low damping, brittle (G); (*3*) strong and high damping, tough (D).

The spread in properties is undoubtedly related to the basic composition of the polyesters. Several physical properties were previously found to correlate well with either of two composition parameters called least-chain length and distance between crosslinks.[3] Least-chain length is defined as the smallest chain which contains all of the components of the polyester, except the styrene, in the proportions given by their mole percentages, as described in Figure 15. Distance between crosslinks is defined as the ratio of least-chain length to moles of unsaturated acid in the least chain.



	1/1 IP/MA	3/4 IP/MA
IP	1	3
MA	1	4
EG	-	1.5
PG	2.1	-
DEG	-	5.8
TBC	0.015	
Co	0.009	
MEKP	0.3	
BPO	0.5	

Fig. 9. Flexural fatigue strength of polyesters (40% styrene) versus the square root of rate of loading (endurance limit given as intercept of ordinate).

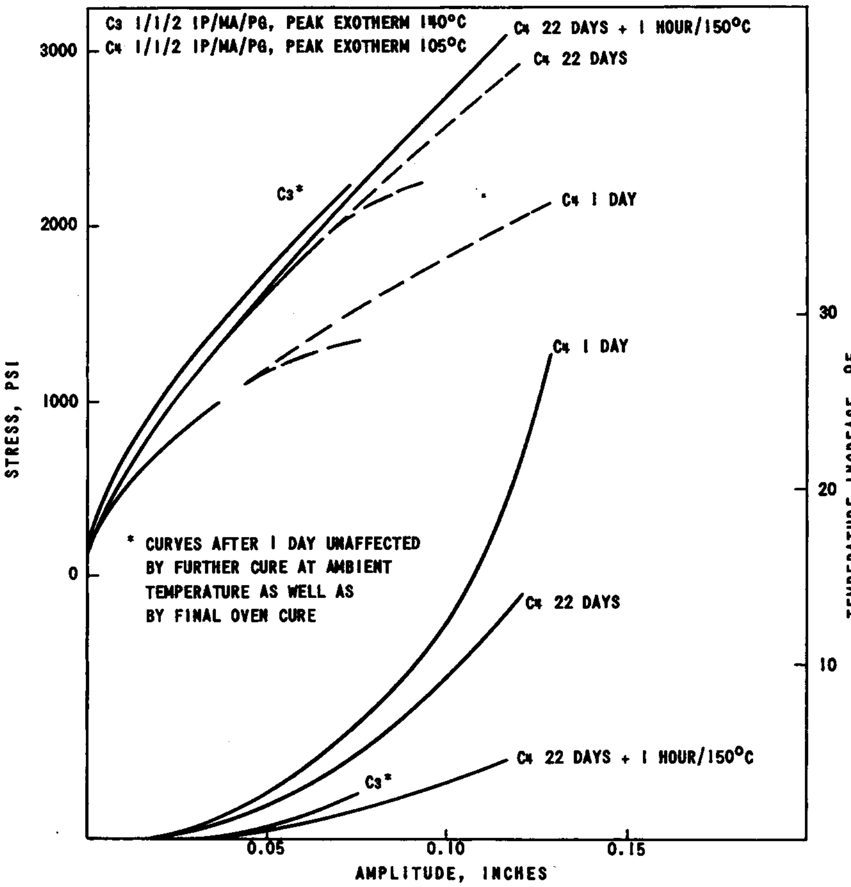


Fig. 10. Effect of rate and degree of cure on stress–deflection curves and temperature profiles of ambient-temperature–cured two-ply 1:1 isophthalic acid/maleic anhydride polyester laminates (load increase 50 psi/min.).

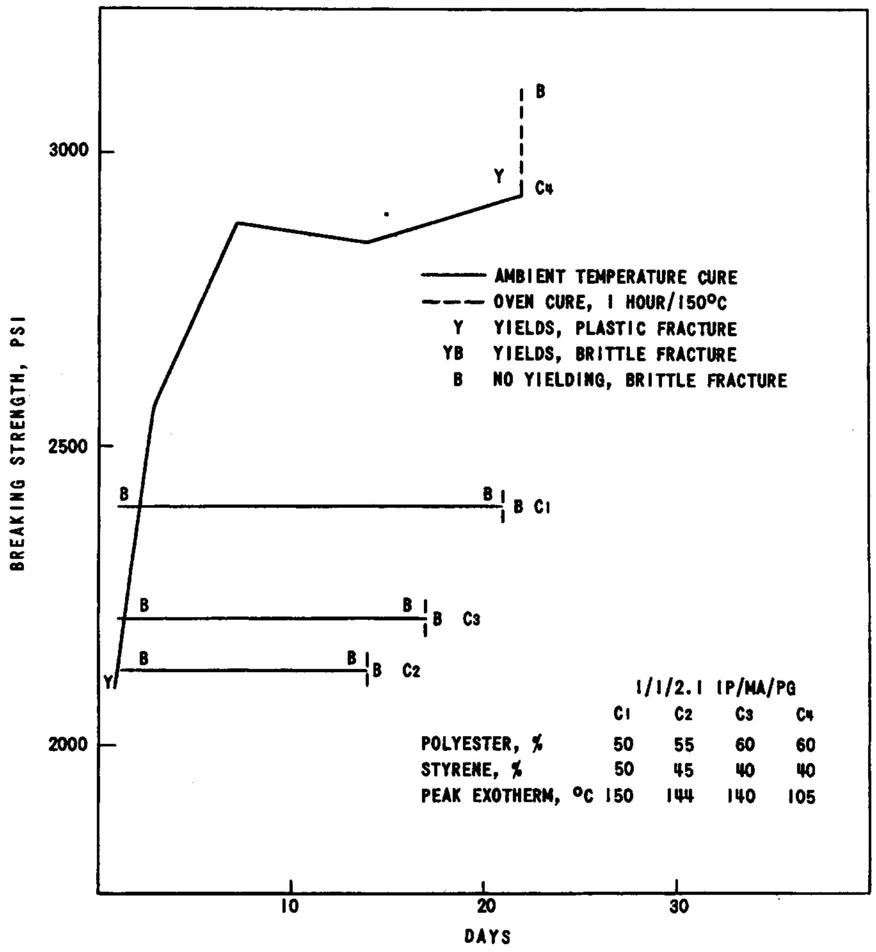


Fig. 11. Flexural fatigue strength versus time of ambient-temperature-cured two-ply 1:1 isophthalic acid/maleic anhydride polyester laminates (load increase 50 psi/min.).

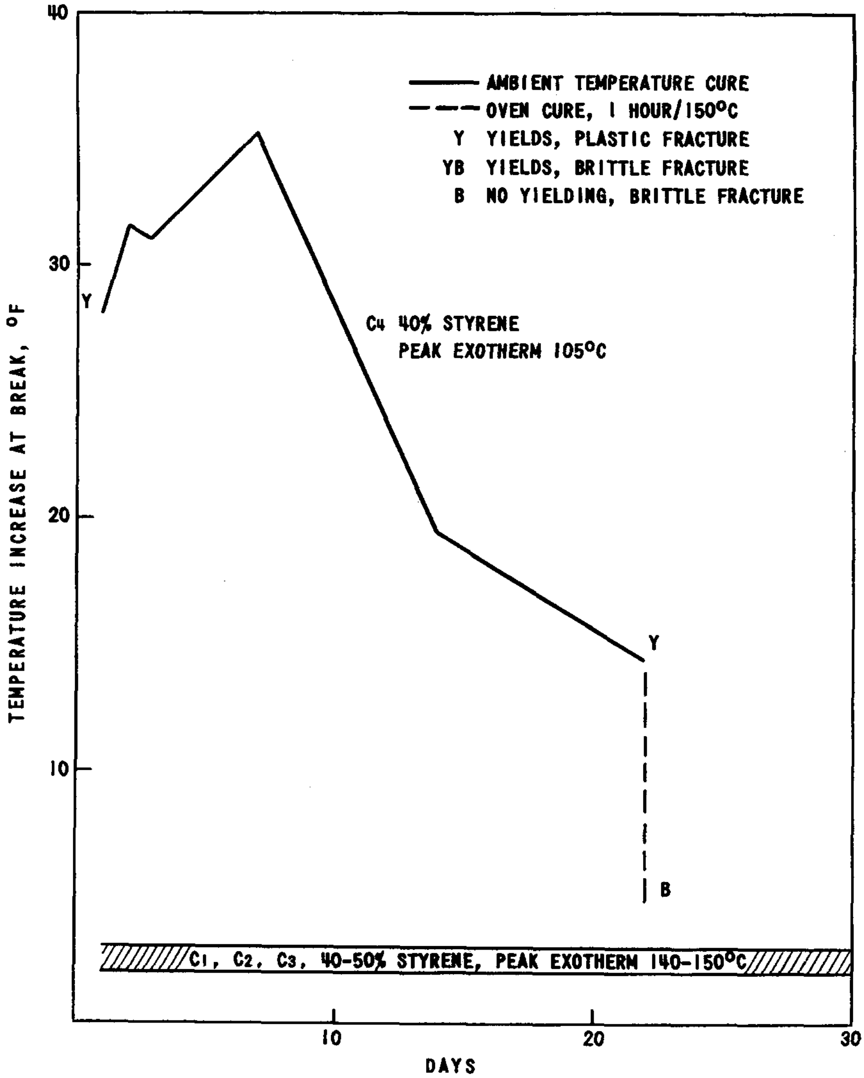
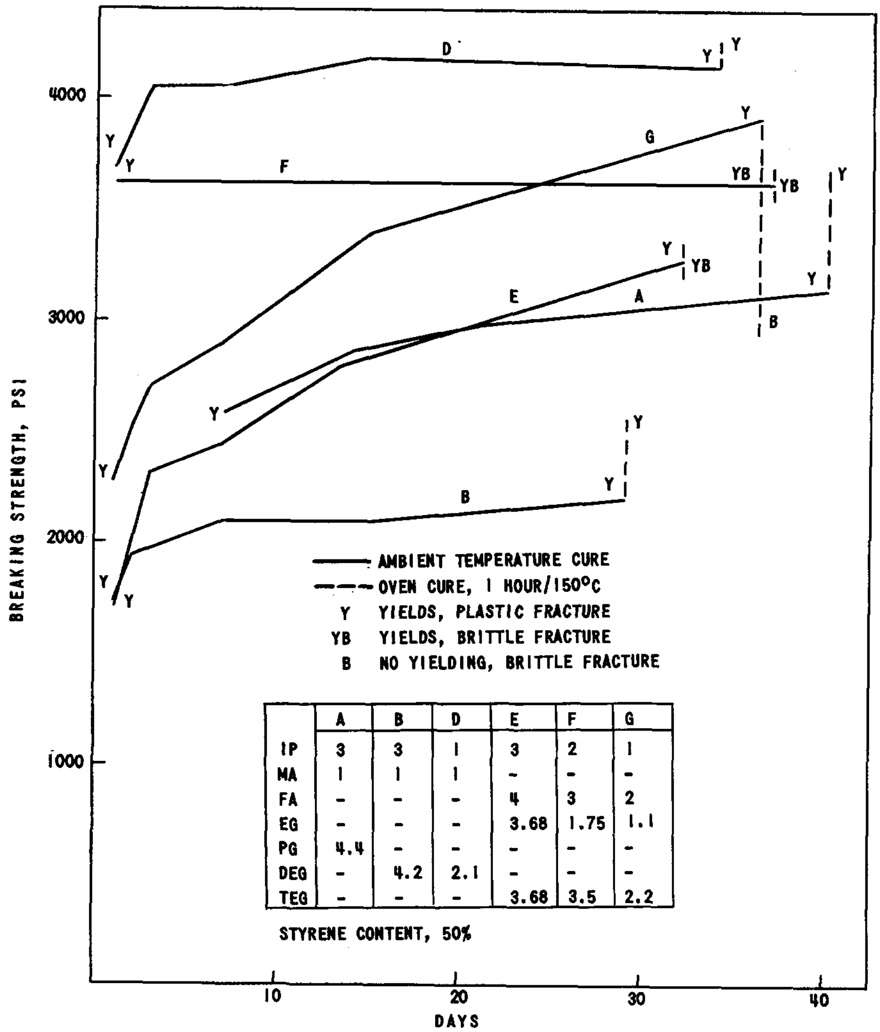
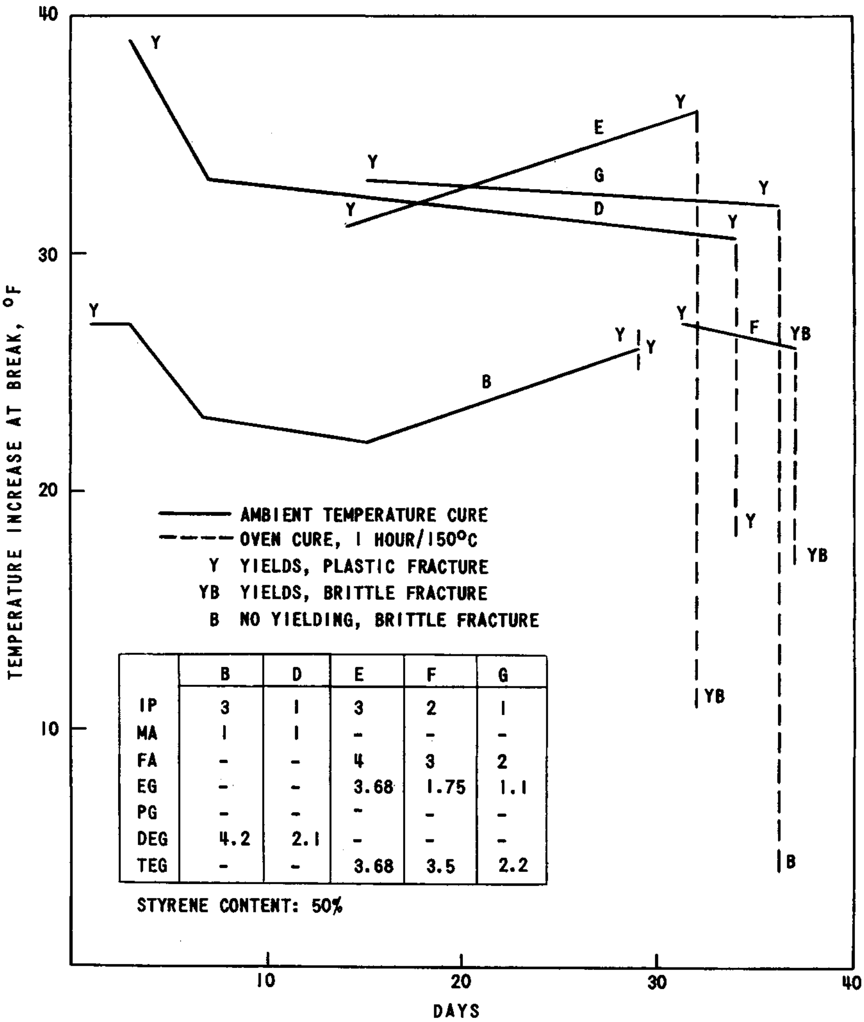


Fig. 12. Damping versus time of ambient-temperature-cured two-ply 1:1:2.1 isophthalic acid/maleic anhydride/propylene glycol polyester laminates (load increase 50 psi/min.).



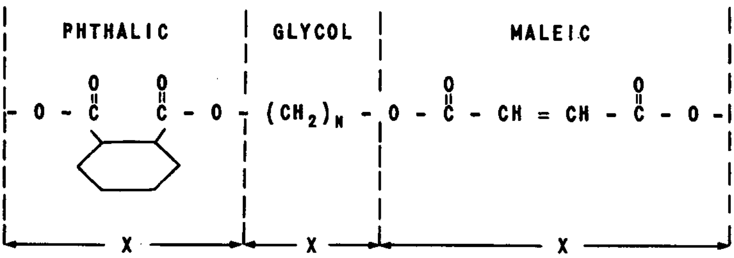
	A	B	D	E	F	G
IP	3	3	1	3	2	1
MA	1	1	1	-	-	-
FA	-	-	-	4	3	2
EG	-	-	-	3.68	1.75	1.1
PG	4.4	-	-	-	-	-
DEG	-	4.2	2.1	-	-	-
TEG	-	-	-	3.68	3.5	2.2

Fig. 13. Flexural fatigue strength versus time of ambient-temperature–cured two-ply 3:1–1:2 isophthalic acid/maleic anhydride (fumaric acid) polyester laminates (load increase 50 psi/min.).



	B	D	E	F	G
IP	3	1	3	2	1
MA	1	1	-	-	-
FA	-	-	4	3	2
EG	-	-	3.68	1.75	1.1
PG	-	-	-	-	-
DEG	4.2	2.1	-	-	-
TEG	-	-	3.68	3.5	2.2

Fig. 14. Damping versus time of ambient-temperature–cured two-ply 3:1–1:2 isophthalic acid/maleic anhydride (fumaric acid) polyester laminates (load increase 50 psi/min.).



LEAST CHAIN LENGTH = ΣXZ

X = LEAST CHAIN LENGTH OF A COMPONENT

Z = MOLE PERCENTAGE OF THE COMPONENT

LENGTH CONTRIBUTION TO THE LEAST CHAIN OF VARIOUS POLYESTER COMPONENTS, AS NUMBER OF C + O IN THE CHAIN DIRECTION.

	X
PA	- 4
IP*	- 5
ADIPIC	- 8
MA/FA	- 6
EG	- 2
PG	- 2
DEG	- 5
TEG	- 8

EXAMPLE:

MOLE RATIO	Z x X	LEAST CHAIN LENGTH
IP 1	24.4 x 5 =	122
MA 1	24.4 x 6 =	144
PG 2.1	51.2 x 2 =	102
4.1	100.0	370

* IP Assigned A Value Of 5 Because Of Slightly Less Rigidity Than PA.

DISTANCE BETWEEN CROSSLINKS CAN BE EXPRESSED AS:

$$\frac{\text{LEAST CHAIN LENGTH}}{\text{MOLES MALEIC AND FUMARIC IN LEAST CHAIN}}$$

i.e., 370 : 24.4 = 15.2 IN THE ABOVE EXAMPLE.

Fig. 15. Derivation of least-chain length. PA = phthalic anhydride; IP = isophthalic acid; MA = maleic anhydride; FA = fumaric acid; EG = ethylene glycol; PG = propylene glycol; DEG = diethylene glycol; TEG = triethylene glycol. Courtesy E. H. Wood.[3]

Figures 16–22 illustrate cases in which these parameters had sufficient effect to establish a trend.

Figures 16 and 17 show that the stiffness decreases with increasing least-chain length over the entire stress range. For elastic dissipation of local stress concentrations, a low resin modulus is probably desirable.

Resin shrinkage on curing increases with least-chain length as well as with increased styrene content, as demonstrated in Figures 18 and 19. Shrinkage provides one of the forces contributing to the adhesion between glass fiber and resin.[4,5] Increased shrinkage is, therefore, probably beneficial as long as the resin is able to support the resulting stress without cracking.

Heat distortion temperatures increase with decreasing distance between crosslinks, as illustrated in Figure 20. Figure 21 shows how flexural strength of unfilled castings increases with heat distortion temperatures up to around 60°C. However, at this temperature, the flexural strength reaches a plateau coincident with a change in mode of fracture from plastic to brittle.

The strength that can be realized under conditions of brittle fracture appears to be very much dependent on the presence of stress raisers such as glass fibers. This is demonstrated in Figure 22 where fatigue strength is plotted against distance between crosslinks. As for the unfilled castings, strength increases with decreased distance between crosslinks as long as

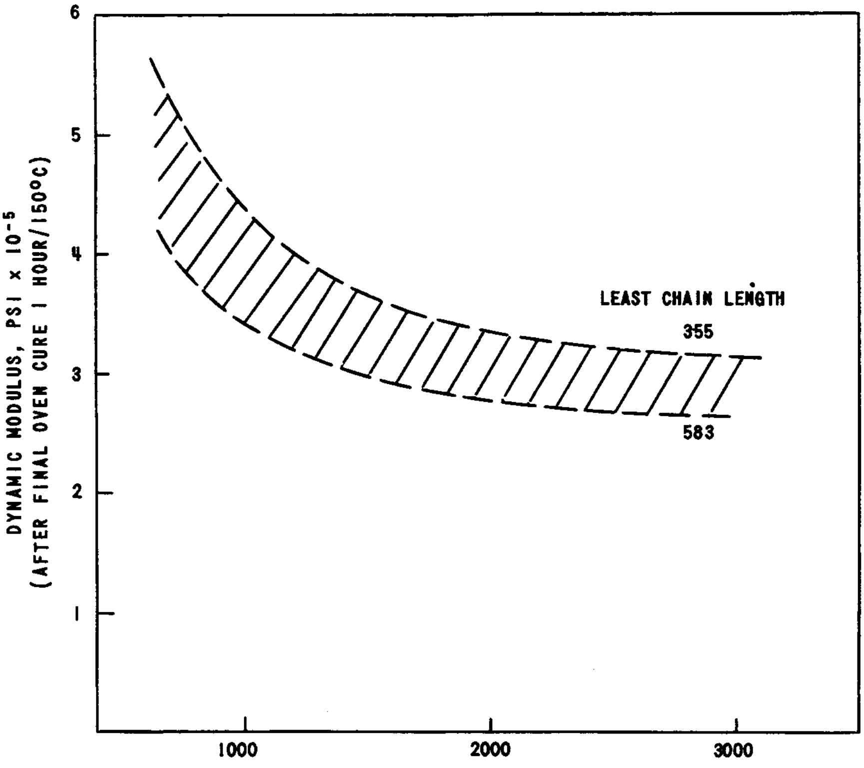


Fig. 16. Dynamic modulus vs. stress relations of ambient-temperature-cured two-ply 3:1–1:2 isophthalic acid/maleic anhydride (fumaric acid) laminates.

the fracture remains plastic. However, when remaining constant for the unfilled castings, strength actually drops with increased brittleness with glass present. Increased brittleness is in Figure 22 manifested also by decreased damping.

In presenting these correlations, several variables were assumed to play a secondary role with respect to the trends. Variables such as molecular weight, branching of the glycol, and styrene content are still very important for the absolute values. With this, as well as the time and temperature dependence of the resins, in mind it is, however, felt that the correlations will be useful for predicting physical properties of such systems.

CONCLUSIONS

A method is described for evaluating flexural fatigue properties of plastic materials with particular reference to unsaturated polyesters modified by

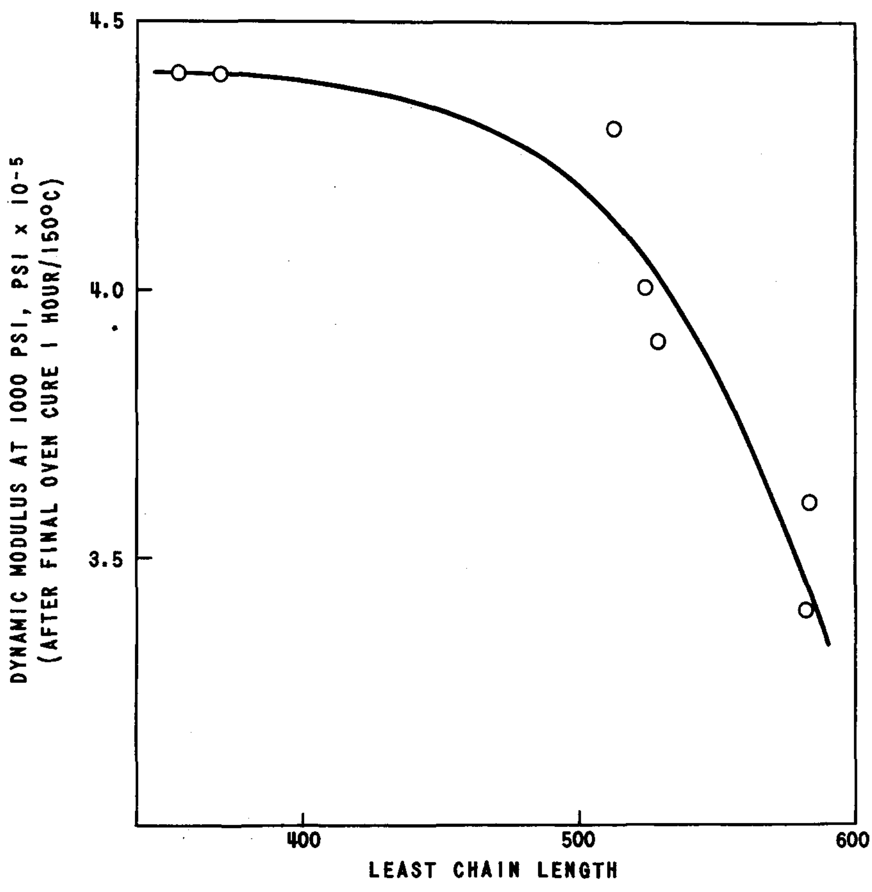


Fig. 17. Dynamic modulus of two-ply laminates versus least-chain length of 3:1–1:2 isophthalic acid/maleic anhydride (fumaric acid) polyesters.

isophthalic acid. With the Sonntag fatigue machine and a modified version of the Prot principle, dynamic parameters and fatigue properties can by this means be readily determined.

Testing of castings with no reinforcement reveals two different modes of resin fracture, brittle and plastic. A plastic fracture implies that the resin yields before breaking. Reproducibility of the results is directly related to the type of fracture, ranging from very good for a plastic resin to very poor for a brittle. Close proximity of yield points and endurance limits for plastic resins confirms the validity of Prot's method of extrapolating the latter parameter.

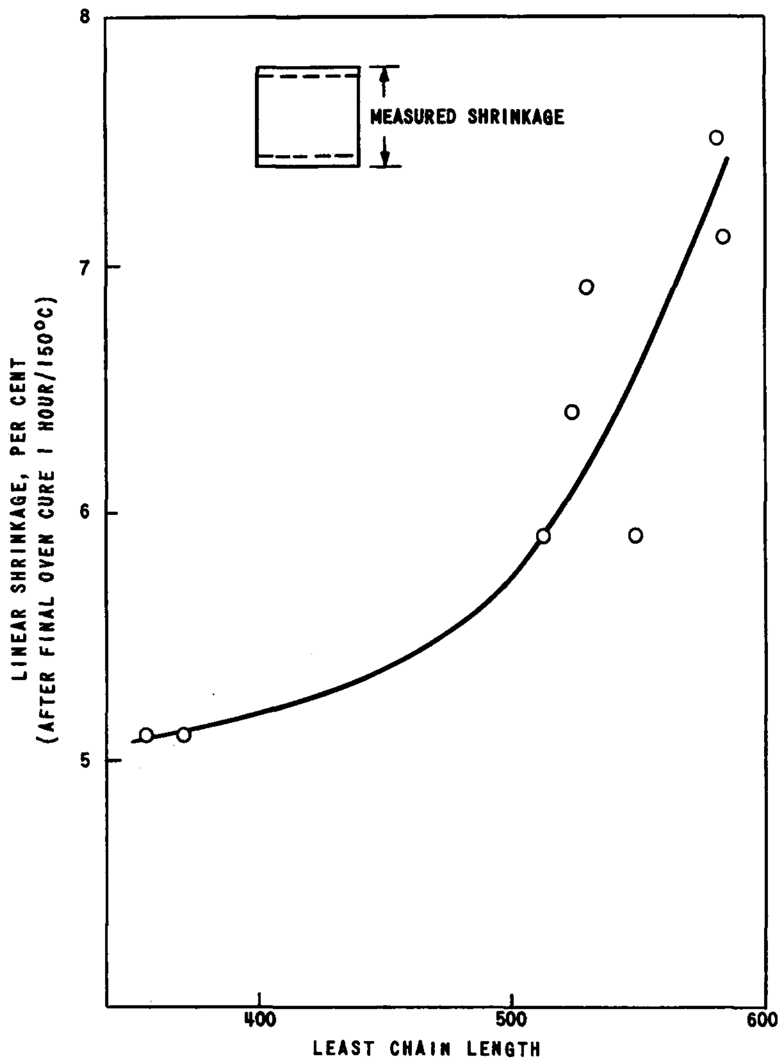


Fig. 18. Shrinkage versus least chain length of 3:1–1:2 isophthalic acid/maleic anhydride (fumaric acid) polyesters (50% styrene).

Incorporation of two layers of glass cloth in positions corresponding to the outermost plies in a laminate shows that failure at the glass–resin interface may be the overriding cause of flex failure of the composite. Both plastic and brittle castings become stiffer in the presence of glass, but only the

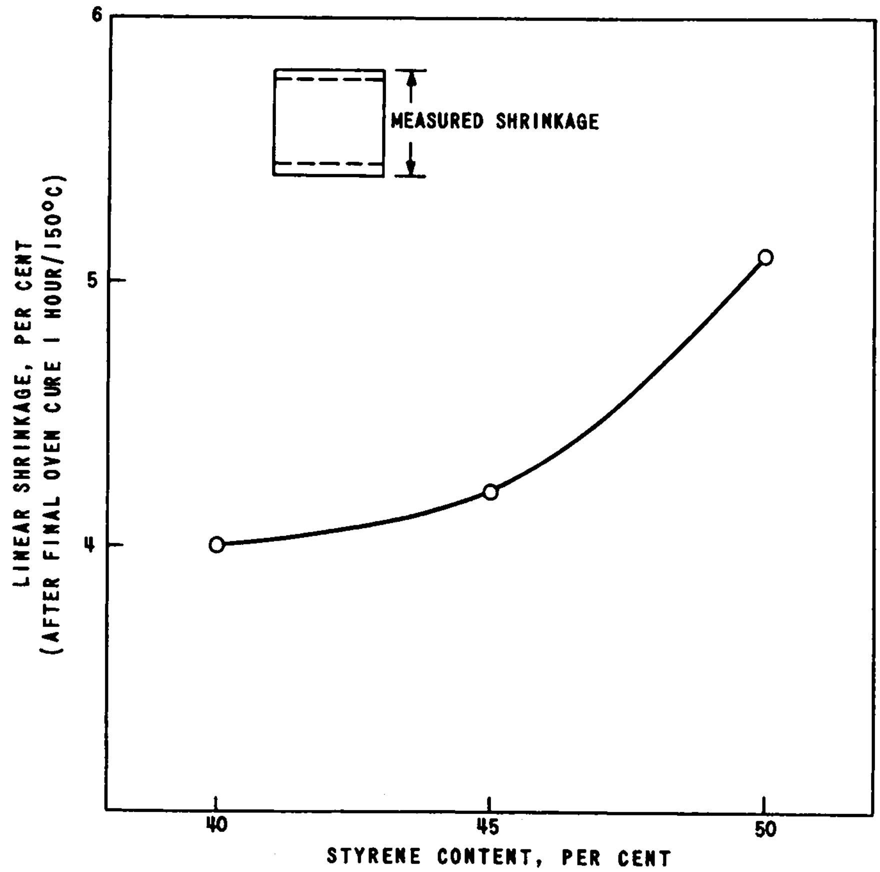


Fig. 19. Shrinkage versus styrene content of 1:1:2.1 isophthalic acid/maleic anhydride/propylene glycol polyester (least chain length 370).

plastic resin is realizing its inherent break deflection to give a correspondingly stronger composite. The brittle composite, on the other hand, fails to reach the break deflection and the strength of the resin itself, indicating breakdown at the glass–resin interface.

Additional plies are expected to increase the stiffness and, correspondingly, the stress to reach the deflection coincident with failure at the outermost plies. Break deflection of the present composites should, therefore, remain the same, provided that the inherent resin properties remain unchanged at the higher glass loadings.

By taking both fatigue strength and damping capacity into account, glass–resin systems can be distinguished as being plastic, brittle, or tough.

For well-cured polyesters, physical properties such as stiffness and cure shrinkage were found to correlate well with the least-chain length. Heat distortion point and strength properties appear to be directly related to distance between crosslinks.

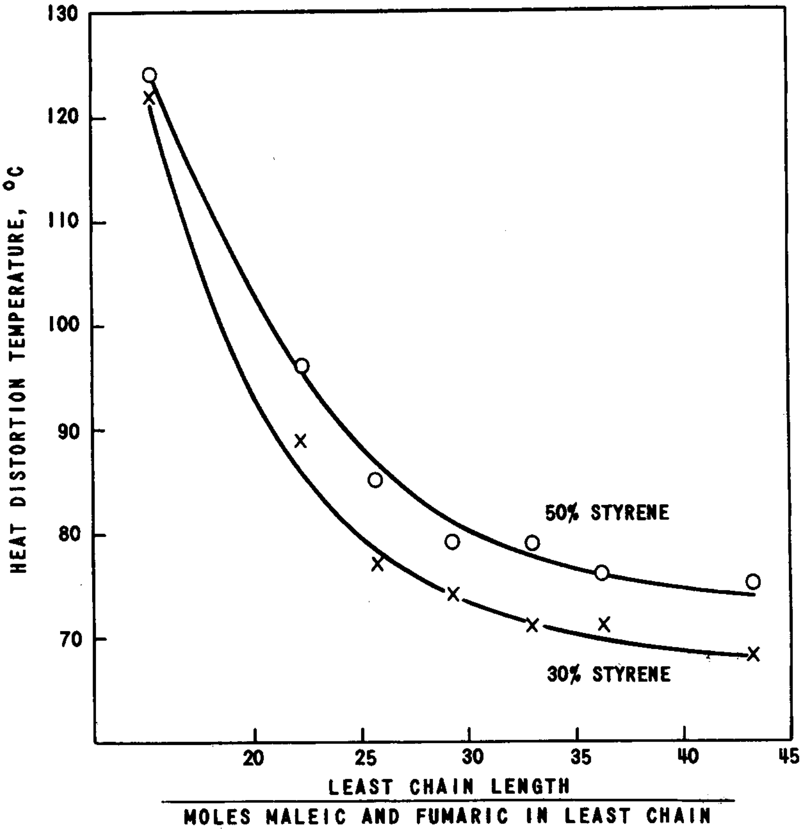


Fig. 20. Heat distortion temperature versus distance between crosslinks of 1:1–5:1 isophthalic acid/maleic anhydride/propylene glycol polyesters. Data courtesy of E. F. Carlston et al.[1]

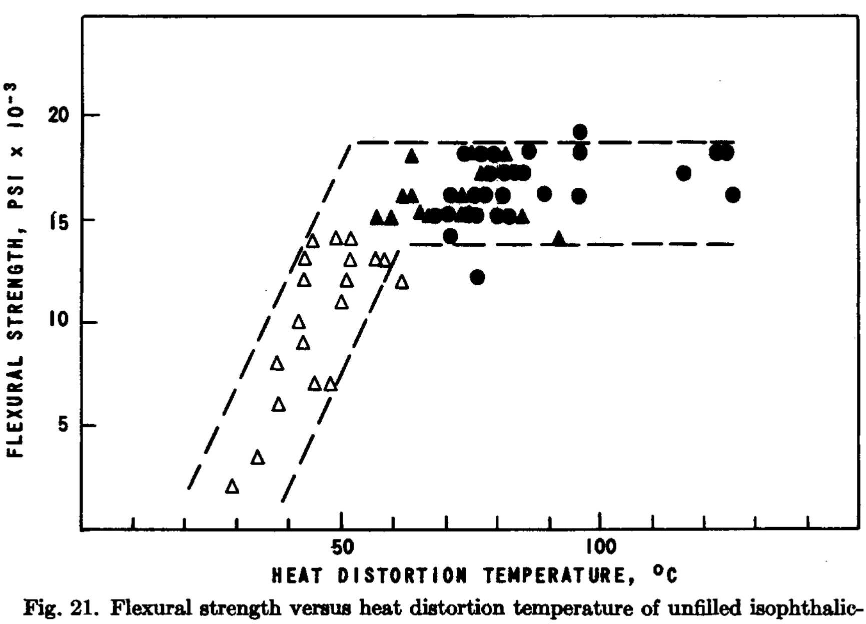


Fig. 21. Flexural strength versus heat distortion temperature of unfilled isophthalic-modified polyesters. (●) Data courtesy of E. F. Carlston et al.[1]; (△, ▲) unpublished data. Filled symbols = brittle fracture; open symbols = plastic fracture.

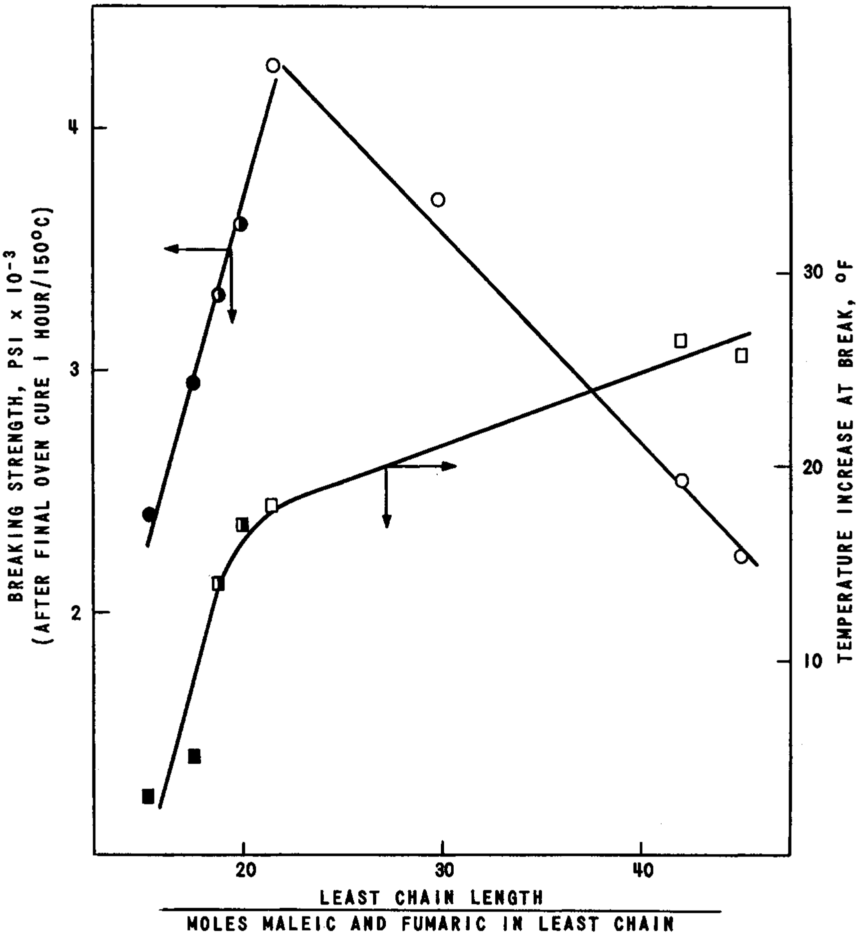


Fig. 22. Flexural fatigue strength and damping of two-ply laminates versus distance between crosslinks of 3:1–1:2 isophthalic acid/maleic anhydride (fumaric acid) polyesters (load increase 50 psi/min.): (○, □) yields, plastic fracture; (◑, ●) yields, brittle fracture; (●, ■) no yielding, brittle fracture.

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Synopsis

A method is described for evaluating flexural fatigue properties of unsaturated polyesters. With the use of the Sonntag fatigue machine and a modified version of the Prot principle, dynamic parameters and fatigue properties can be readily determined. Testing of castings with no reinforcement reveals two different modes of resin fracture, brittle and plastic. A plastic fracture implies that the resin yields before breaking. Reproducibility of the results is directly related to the type of fracture, ranging from very good for a plastic resin to very poor for a brittle. Close proximity of yield points and endurance limits for plastic resins confirms validity of Prot's method of extrapolating the latter parameter. Incorporation of two layers of glass cloth in positions corresponding to the outermost plies in a laminate shows that failure at the glass–resin interface may be the overriding cause of laminate breakdown. Both plastic and brittle resins become stiffer in the presence of glass, but only the plastic resin is realizing its inherent strength to give a stronger reinforced casting. The brittle resin is, on the other hand, weaker with glass present because of inability to dissipate local stress concentrations at the warp–filling crossovers. The break amplitude is a particularly significant parameter because it is expected to be the same in a normal laminate as in these castings with only the outermost plies present. Additional plies would merely increase stiffness and, correspondingly, the stress to reach amplitude coincident with failure at the outermost plies. Use of relatively thick test bars (0.5 in.) permits insertion of a thermocouple in the neutral plane without affecting dynamic properties. Measurement of the temperature rise during flexing allows assessment of the damping capacity of the glass–resin system, which is of particular importance for resonance fatigue. By this means, three different types of glass–resin systems could be distinguished: (*1*) weak and high damping (plastic), (*2*) strong and low damping (brittle), (*3*) strong and high damping (tough). For a particular resin, the behavior is determined by the basic composition as well as by degree of cure. For well-cured polyester samples, several links were found between dynamic parameters, such as stiffness, fatigue strength and damping, and basic composition. Distance between crosslinks in the polyester backbone thus appears to have a direct bearing on strength and damping. Such relationships are valuable in that they make possible predictions of the fatigue behavior of a given polyester formulation.

Résumé

On décrit une méthode pour évaluer les propriétés, dues à la fatigue de la flexion des polyesters insaturés. Utilisant la machine de fatigue Sonntag et une version modifiée du principe de Prot, on peut déterminer aisément de cette façon des paramètres dynamiques et des propriétés dues à la fatigue. Des tests de coulées sans renforcement révèlent deux modes différents de fracture des résines, fragile et plastique. Une fraction plastique implique que la résine fléchit avant de casser. La reproducibilité des résultats est directement liée au type de fracture; elle est très bonne pour une résine plastique mais très mauvaise, par contre, pour une résine fragile. La proximité des limites de résistance et des limites d'endurance pour les résines plastiques, confirme la validité de la méthode de Prot pour l'extrapolation du dernier paramètre. L'incorporation de deux couches de tissu de verre dans des positions correspondant aux plis extérieurs dans un échantillon laminaire démontre qu'une interruption à l'interface résine–verre peut être la cause principale de la rupture de l'échantillon laminaire. Les deux résines plastiques et fragiles deviennent plus raides en présence de verre, mais seule la résine plastique réalise sa résistance inhérente pour donner une coulée plus forte et renforcée. La résine fragile par contre, est plus molle en présence de verre, à cause de l'inaptitude à dissiper leur concentration en tension locale et les frottements charge–résine. L'amplitude de cassure est un paramètre particulièrement significatif parce qu'on croit qu'elle est la même dans un échantillon laminaire normal que dans ces coulées où seulement les plis extérieurs sont présents. Des plis additionnels n'augmenteraient rien que la rigidité et d'une manière correspondante la tension pour atteindre l'amplitude correspondante au détachement des plis extérieurs. L'emploi de barres expérimentales relativement épaisses (0.5 pouce) permet l'insertion d'un thermocouple dans le plan neutre sans affecter les propriétés dynamiques. La mesure de l'augmentation de température pendant la flexion permet la détermination de la capacité d'amortissement dans

le système verre–résine; ceci à une importance particulière pour la fatigue due à la résonance. De cette façon on pouvait distinguer trois types différents de systèmes verre–résine: (*1*) mou et amortissement élevé (plastique); (*2*) dur et amortissement faible (fragile); (*3*) dur et amortissement élevé (coriace). On a déterminé le comportement d'une résine particulière par sa composition de base ainsi que par son degré de vulcanisation. Pour des échantillons de polyesters bien vulcanisés, on a trouvé plusieurs relations entre les paramètres dynamiques, comme la rigidité, la résistance à la fatigue, l'amortissement et la composition de base. Ainsi il semble que la distance entre les liaisons transversales dans la chaîne principale exerce une influence directe sur la force et l'amortissement. De telles relations sont précieuses parce qu'elles permettent des prédictions concernant le comportement à la fatique d'une formulation donnée de polyester.

Zusammenfassung

Eine Methode zur Ermittlung der Biegungs-Ermüdung von ungesättigten Polyestern wird beschrieben. Unter Benützung der Ermüdungsmaschine von Sonntag und einer modifizierten Version des Protschen Prinzips können auf diese Weise dynamische Parameter und Ermüdungserscheinungen leicht bestimmt werden. Prüfung von unverstärkten Gussstücken zeigt zwei verschiedene Brucharten eines Harzes, spröden und plastischen Bruch. Plastischer Bruch bedeutet, dass das Harz vor dem Bruch fliesst. Die Reproduzierbarkeit der Ergebnisse steht in direkter Beziehung zum Bruchtyp; sie erstreckt sich von "sehr gut" bei einem plastischen Harz zu "sehr schlecht" bei einem spröden. Die enge Nachbarschaft zwischen Fliesspunkt und Beanspruchungsgrenze für plastische Massen bestätigt die Brauchbarkeit der Protschen Methode zur Extrapolation letzterer Grösse. Der Einbau von zwei Schichten von Glasgewebe in den äussersten Lagen eines geschichteten Materials zeigt, dass ein Versagen an der Glas–Harzgrenzphase die überwiegende Ursache für den Zusammenbruch des Materials sein kann. Sowohl plastische als auch spröde Harze erhalten in Gegenwart von Glas eine grössere Steifigkeit, aber nur beim plastischen Harz drückt sich diese spezifische Festigkeit in der Bildung von verstärkten Gussstücken mit höherer Festigkeit aus. Das spröde Harz ist dagegen bei Gegenwart von Glas schwächer, wegen der Unfähigkeit eine lokale Spannungskonzentration an den Füllungsstoffüberwerfungen zu zerstreuen. Die Bruchamplitude bildete einen besonders charakteristischen Parameter, da sie in einem normalen Schichtstoff die gleiche sein sollte, wie in Gussstücken mit lediglich den äussersten Schichten. Zusätzliche Schichten würden nur die Steifigkeit erhöhen und damit die zur Erreichung der mit dem Zusammenbruch an den äussersten Schichten zusammenfallenden Amplitude notwendige Spannung. Benützung relativ dicker Teststäbe (0,5 inch) erlaubt die Anbringung eines Thermoelements in der neutralen Ebene ohne Beeinflussung der dynamischen Eigenschaften. Messung des Temperaturanstieges während der Biegung gestattet die Ermittlung der Dämpfungskapazität des Glas–Harzsystems, die besondere Bedeutung für die Resonanzermüdung besitzt. Auf diese Weise konnten drei verschiedene Typen von Glas–Harzsystemen unterschieden werden: (*1*) Schwach und hohe Dämpfung (plastisch), (*2*) Stark und niedrige Dämpfung (spröde), (*3*) Stark und hohe Dämpfung (zähe). Für ein gegebenes Harz wird das Verhalten sowohl durch seine Zusammensetzung als auch durch den Aushärtungsgrad bestimmt. Bei gut ausgehärteten Polyesterproben wurden einige Beziehungen zwischen dynamischen Parametern, wie Steifigkeit, Ermüdungsfestigkeit und Dämpfung, und der Zusammensetzung gefunden. So scheint der Abstand der Vernetzungsstellen in der Polyesterkette einen direkten Einfluss auf Festigkeit und Dämpfung zu haben. Solche Beziehungen sind insofern wertvoll, als sie die Vorherbestimmung des Ermüdungsverhaltens eines gegebenen Polyesteransatzes möglich machen.

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