Validity of the SWT parameter for woven – roving GFRP subjected to torsional or bending moments

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The Smith-Watson-Topper (SWT) parameter has allowed a great reduction in the number of tests required to estimate the effect of mean stress on the fatigue life of metals, and some composites for which it was validated. This is because; if the SWT parameter is found to be valid, then plotting it instead of the maximum or the amplitude stress component against the number of cycles to failure tends to plot a single curve, when having variable mean stresses or stress ratios. Torsional fatigue tests were performed on thin-walled tubular specimens, made from woven-roving Glass Fibre-Reinforced Polyester (GFRP) with two fibre orientations ($[\pm 45^o]_{2s}$ and $[0,90^o]_{2s}$), at different negative stress ratios, R = - 1, -0.75, -0.5, -0.25, 0. Besides, the validity of the SWT parameter was also check for similar specimens subjected to bending moments. It was found that the SWT parameter is valid for both cases, torsional or bending fatigue loading, resulting in a great reduction in time and effort when studying a similar case in future.

أن استخدام معامل SWT فى تقيم سلوك الكلال فى المعادن وفى بعض المواد المؤلفة يؤدى إلى تناقص كبير فى عدد التجارب المطلوبة لدراسة تأثير الاجهاد المتوسط على عمر الكلال. لانه فى حالة فعالية هذا المعامل فأننا بدلا من توقيع النتائج فى صورة علاقة بين الاجهاد الاقصى أو الاجهاد المتغير مع عدد الدورات حتى الانهيار عند كل نسبة اجهاد أو كل اجهاد متوسط فأننا باستخدام هذا المعامل نحصل على منحنى وحيد مما يسبب وفرا كبيرا جدا فى الوقت. وقد تم اختبار عينات اسطوانية رفيعة السمك مصنعة من البوليستر المدعم بالياف زجاجية منسوجة شبكيا عند زوايا اتجاه الالياف (صفر ، ٩٠°) و (± ٤٥°) عند نسب اجهادات -١، -٠,٧٥، -٠,٥، -٠,٢٥، صفر . كما تم تطبيق هذا المعامل فى تجارب الكلال على نفس العينات والمعرضة لعزم انحناء بدلا من عزم التواء ووجد ان المعامل SWT صالح فى كلتا الحالتين ليعطى منحنى وحيد مع عمر الكلال.

Keyword*:* Glass fiber, Reinforced polyester, Tensional / bending fatigue, SWT Parameter, Mean stress

1. Introduction

For metals, it was found that, plotting the fatigue life against the SWT parameter, which represents the value of $\sqrt{\sigma_{max}\sigma_a}$, when having normal stresses with different mean values, tends to plot a single curve. It was subsequently possible to characterize the complete mean stress effect for a given metal with only a single stress ratio [1].

Conle and Ingall [1] tried to validate the same parameter for composite materials to account for the effect of mean stress in axially loaded cases. They used un-notched, axially loaded GFRP flat specimens, with V_f = 60 %, fibre orientation of [± 45°] at room temperature. They found that:

1. The SWT parameter will not work directly for composites as for metals, because of the multiplicity of failure modes. For axially loaded specimens we must use the form ($\sqrt{\sigma_{max}\sigma_a}$) for tensile failure, while use the form -$\sqrt{\sigma_{max}\sigma_a}$) for compressive failure.
2. Other types of fatigue loading must require further experimental investigations. In other words, the SWT parameter may and may not work in other cases.

Sauer [2] examined un-reinforced axially loaded polystyrene samples, at several tensile mean stress values. They made two groups of tests; the first one was with constant amplitude stress and different mean stresses resulting in varying maximum stresses, and the second group was with constant maximum stress with different combinations of mean and amplitude stresses. When plotting the test results, they used three forms of S-N curves; they used (σ_{max}), (σ_a) or

($\sqrt{\sigma_{max}\sigma_a}$) as the ordinate versus the number of cycles to failure as abscissa. The plots indicated that, using the ($\sqrt{\sigma_{max}\sigma_a}$), which is the SWT parameter, is slightly better than using ((σ_{max}) and both are better than (σ_a). This was because ($\sqrt{\sigma_{max}\sigma_a}$) succeeded in showing the effect of mean stress in both types of tests.

Ryder and Walker [3] performed axially loaded fatigue tests with various tensile mean stresses on un-notched quasi - isotropic T300/934 graphite - epoxy specimens. Using the same procedure as Sauer J.A. et al. [2], they found that, in this case, both of (σ_a) and ($\sqrt{\sigma_{max}\sigma_a}$) represent the data equally well and better than (σ_{max}).

Finally, both of Sauer [2] and Ryder and Walker [3] have found that the SWT parameter can be used exactly in the same manner as it is applied in metals, when expecting a tensile failure mode.

Smith and Owen [4] studied the axial fatigue behaviour of low and high reactivity polyester, chopped strand mat specimens. They found that the SWT parameter is a suitable method in depicting the fatigue life of both types of materials under tensile and zero mean stresses. When using compressive mean stresses, they found that this parameter did not work in the same manner, and it failed in representing the test data. They attributed this difference to various microscopic effects that arise in the case of compression, such as fibre or specimen buckling.

Schuetz and Gerharz [5] studied the possibility of differences between tensile and compressive failure mechanisms in axially loaded carbon fibre reinforced plastic. Their tests covered the range of stress ratios from 0.1 to –5, and indicated that the compressive mean stress results are not well represented by the ($\sqrt{\sigma_{max}\sigma_a}$) parameter. When they used ($-\sqrt{|\sigma_{min}|\sigma_a}$) instead, the results were better represented, but the lack of further information regarding the failure modes made it impractical to ensure the use of this new form.

Other investigations were done successfully on using the form ($\sqrt{\sigma_{max}\sigma_a}$) in tension and ($-\sqrt{|\sigma_{min}|\sigma_a}$) in compression. Ramani and Williams [6] checked their applicability on [0,30°] graphite / epoxy specimens and Sturgeon and Rhodes [7] on [±45°] carbon / epoxy specimens. They both found that using ($\sqrt{\sigma_{max}\sigma_a}$) for tensile and zero mean stresses and ($-\sqrt{|\sigma_{min}|\sigma_a}$) for compressive mean stresses work very well for the studied cases.

The SWT parameter has been also applied by Gravett P. W. [8] for predicting the fatigue life of Sc S-6 / *Ti*-15-3 composite under isothermal fatigue. The life prediction was found to be valid for any load – temperature cycle as well as for different fibre volume fractions. But, he drew the attention to a great important point; which is the approach of using the SWT parameter is valid for conditions of matrix-dominated failure mode, as usually the matrix being ductile.

2. Experimental work

Most researchers use the stress ratio (*R*) when dealing with the effect of mean stress under different loading conditions [1, 9, 10, 11, 12]. The stress ratio (*R*) is defined to be the ratio between the minimum and maximum applied stresses. Consequently, torsional fatigue tests were performed on thin-walled tubular specimens at different negative stress ratios, *R* = - 1, -0.75, -0.5, -0.25, 0. The applied torque was measured via a load cell, fixed on one of the grippers, consisting of four active strain gauges, forming a full bridge. The signal is amplified and displayed on an oscilloscope and the whole system was calibrated.

2.1. Testing machine

The used testing machine was previously designed by Abouelwafa M.N. et al. [13] and used by other researchers in similar works [9, 14, 15, 16]. It is a strain controlled testing machine, rotating at a constant speed of 525 rpm (8.75 Hz); and capable of performing pure

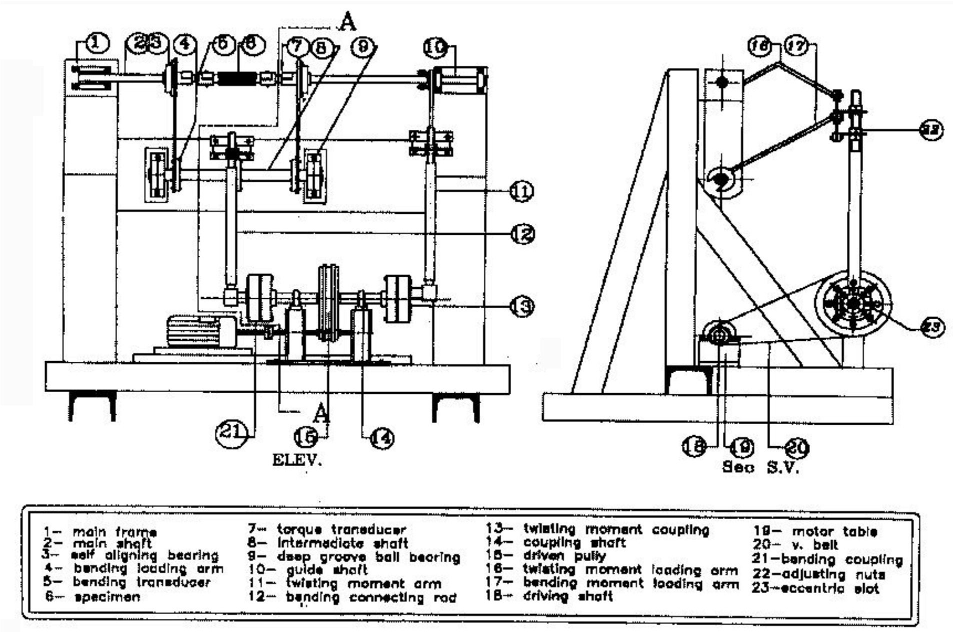

Fig. 1. General layout of the testing machine.

Table1
Properties of used materials [15, 21, 22]

Woven–roving E-glass fibres		Polyester	
Property	Value	Property	Value
Density	2551 kg / m^3 [22]	Density	1161.3 kg / m^3 (measured)
Modulus of elasticity	E = 76 GPa [23]	Modulus of elasticity	E = 3.5 GPa [23]
Poisson's ratio	υ = 0.37 [23]	Poisson's ratio	υ = 0.25 [23]
Tensile strength	3.45 GPa [22]	Gel time at 25 °C	20 min.
Average mass / area	600 gm / m^2	Viscosity	0.45 Pa.s [15]
Average thickness	0.69 mm [15]	Percentage of Styrene	40 % [15]
Weave	Plain	Trade name	Siropol 8340

torsion, pure bending, or combined torsion and bending (in-phase or out-of-phase) fatigue tests. Fig. 1 shows a general for the machine, the loading systems (torsion and bending) are independent, and have the facility to apply different mean stresses. The specimen is subjected to a uniform load, along its whole length, through a gripping system consisting of two halves that enclose the specimen in between.

2.2. Specimens

Thin-walled tubes made from two layers of woven – roving E – glass / polyester with two fibre orientations, $[\pm 45^o]_{2s}$ and $[0,90^o]_{2s}$, were used with a fibre volume fraction (V_f) ranging from 55 % to 65 %. This range was used in previous works [14, 15, 17] and has proved its suitability to ensure good adhesion between fibres and matrix, good strength and acceptable mechanical properties. Table 1 shows the properties of the used materials. Cobalt Naphthenate (6 % solution) was used as an accelerator in a percentage of 0.2 % by volume and Methyl Ethyl Ketone (MEK) peroxide as a catalyst in a percentage of 2 %, by volume [9, 14, 15, 18]. Cross-linking and curing took place at ambient conditions fig. 2 shows the nominal dimensions of the used specimens, with tolerance ± 0.1 mm, which were measured after complete curing and being within the standard dimensions [9, 14, 15]. The thickness of the tube ends were

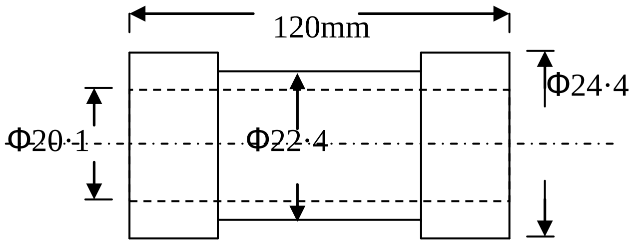

Fig. 2. Dimensions of used specimens.

built up by additional two layers to avoid gripping problems, and gradually introduce the load so that failure occurs in the central, uniformly stressed portion of the tube [19, 20].

2.3. Stress state

Specimens are subjected to torsional fatigue moments with different mean values. Being cylindrical in shape, there global stress (τ_{xy}) may be found from the following equation:

$$\tau_{xy} = \frac{Tr}{J} \ .$$

Where:

T	is the applied torque ($T = T_m + T_a \sin \omega t$),
T_m and T_a	are the mean and amplitude torques respectively,
(ωt)	is the twisting angle,
J	is the second polar moment of area; $J = \frac{\Pi}{32}\left(d_o^4 - d_i^4\right)$,

(d_o) and (d_i) are the outer and inner diameters of the specimen, respectively, and

$r = d_o / 2$.

The [± 45°]$_{2s}$ specimens had a tension-compression local stress state, $\sigma_1 = - \sigma_2 = \tau_{xy}$ and $\sigma_6 = 0$. While the [0,90°]$_{2s}$ specimens had a pure local shear stress state, $\sigma_1 = \sigma_2 = 0$ and $\sigma_6 = \tau_{xy}$.

3. Test results

It is important to note that, in order to avoid any misleading data, only the specimens that had their failure features within the accepted gauge section, the middle third of the whole length, were considered; while those that seemed to have their failure due to any gripping problems were excluded. Each experimental data point was obtained by considering the average of three specimens tested under the same conditions.

3.1. Static tests

Static torsional tests were performed on the tubular specimens of both orientations, [± 45°]$_{2s}$ and [0,90°]$_{2s}$, in order to find out their ultimate global shear strengths (S_{us}), which was found to be as follows;
(S_{us}) of the [0,90°]$_{2s}$ specimens = 47 MPa
(S_{us}) of the [±45°]$_{2s}$ specimens = 76 MPa

3.2. Fatigue tests

All specimens were tested under ambient conditions and constant frequency of 8.75 Hz. The data points were used to plot the SWT parameter for each of the two fibre orientations, against the number of cycles to failure. Failure was considered to occur when the load reading decreased by about 20% of its original value. In other words, 20 % reduction in the strength of the specimen will represent failure. Figs. 2 and 3 show these results for the [±45°]$_{2s}$ and [0,90°]$_{2s}$ specimens, respectively; and the power-law form: SWT = cN^d was used for fitting these data points that gave acceptable results.

4. Discussion

4.1. Present studied case

Having good and acceptable correlation factors for the SWT parameter in both fibre orientations showed the validity of this parameter in the studied case. Therefore, negative stress ratios do not affect the value of the SWT parameter. Besides, the ratio between the constant (c) to the static torsional strength of the corresponding fibre orientation resulted in a good promising results. This ratio was found to be nearly constant for both orientations.
$(c)_{[\pm 45]} \ / \ (c)_{[0,90]} = 1.77$,
$(c/S_{us})_{[\pm 45]} = 1.185$ and $(c/S_{us})_{[0,90]} = 1.083$.

4.2. SWT parameter for similar specimens under bending moments

Trying to check the validity of the SWT parameter to other loading conditions, data was obtained from the work of Sharara A. I. [9]. Woven-roving GFRP thin-walled tubular specimens with (V_f) ranging from 50 % to 64 % and two fibre orientations, $[\pm45^o]_{2s}$ and $[0,90^o]_{2s}$, were tested under uniaxial bending stress with the same stress ratios as in this work. The static bending strength (S_u) was 118.82 MPa for the $[\pm45^o]_{2s}$ specimens and 187.123 MPa for the $[0,90^o]_{2s}$ specimens. His data points were used to plot the SWT parameter against the number of cycles to failure, as shown in fig. 4 and fig. 5.

Having smaller correlation factors than the present studied case may be attributed to the relatively small numbers of data points available in his work.

The ratio between the parameter (c) to the static bending strength (S_u) of the corresponding fibre orientation was found to be nearly

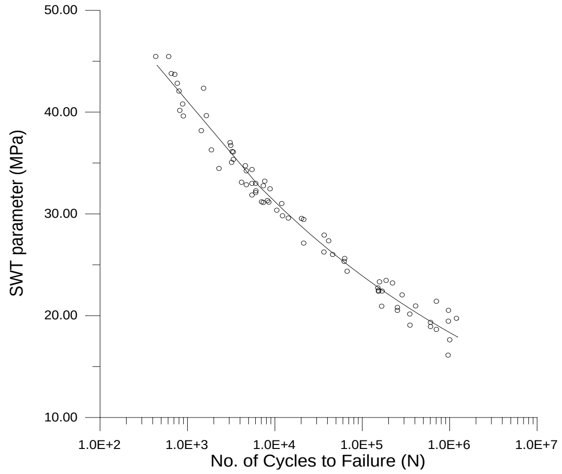

Fig. 2. SWT parameter for the $[\pm45^o]_{2s}$ specimens SWT= 90.1198 $N^{-0.115227}$, correlation factor = 0.974416.

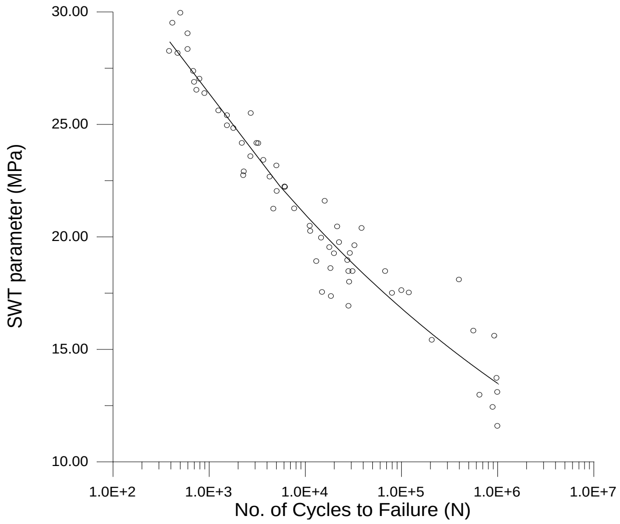

Fig. 3. SWT parameter for the $[0,90^o]_{2s}$ specimens, SWT = 50.9027 $N^{-0.0961729}$, correlation factor = 0.923621.

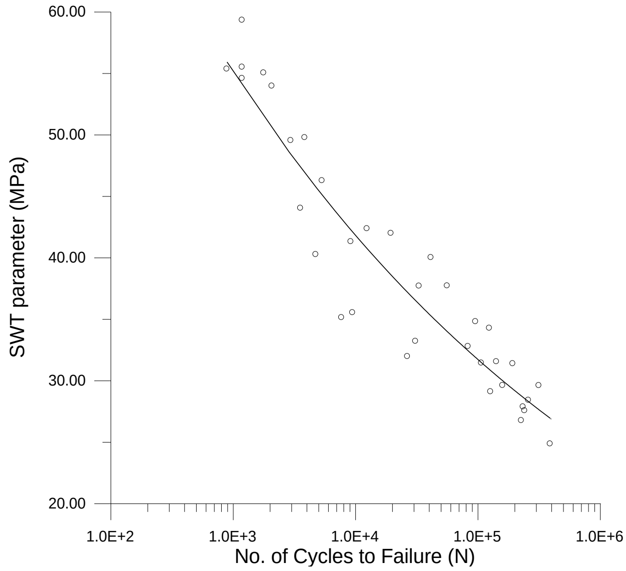

Fig. 4. SWT parameter for the $[\pm45^o]_{2s}$ specimens subjected to bending moments. SWT = 126.573 $N^{-0.120191}$, correlation factor = 0.88978.

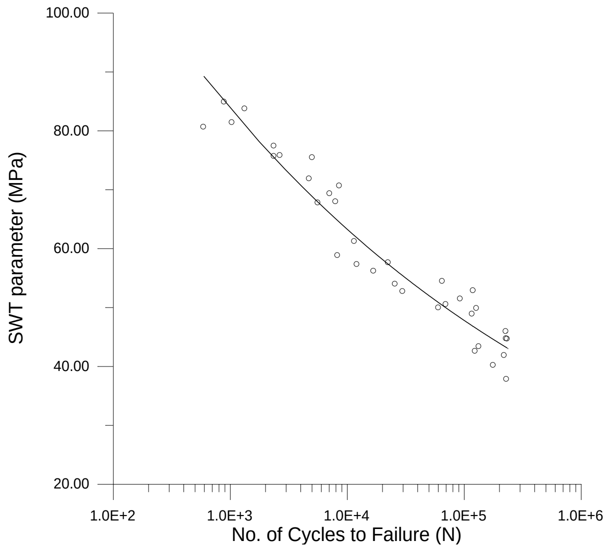

Fig. 5. SWT parameter for the $[0,90^o]_{2s}$ specimens subjected to bending moments SWT = 194.637 $N^{-0.12199}$, correlation factor = 0.927058.

constant for both orientations, as was found in our case.
$(c)_{[0,90]}$ / $(c)_{[\pm 45]}$ = 1.54,
$(c\ /\ S_u)_{[\pm 45]}$ =1.0652 and $(c\ /\ S_u)_{[0,90]}$= 1.0402.

5. Conclusions

1. The SWT parameter ($\sqrt{\tau_{max}\,\tau_a}$) is valid for woven-roving GFRP with [±45°] and [0,90°] orientations, tending to plot a single curve when plotted versus the number of cycles to failure for negative stress ratios, for the present case and also for bending fatigue conditions.

This conclusion will result in a great reduction in effort and required data in any future work. Performing, only, the completely reversed fatigue test (R = -1) and using the SWT parameter, which has the value of $\sqrt{2}\,\tau_a$ in this case, will be sufficient to find out the strength of the material under any negative stress ratio.

2. Using the power formula: SWT = cN^d has resulted in having a nearly constant ratio between (c) and the corresponding static strength for both fibre orientations, being equal to 1.08 for torsional loading and 1.04 for bending loading. One can consider it equal to unity for more conservative design point of view.

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