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MODELLING OF ULTIMATE ELASTIC WALL STRESS (UEWS) TESTS FOR GLASS FIBRE-REINFORCED EPOXY COMPOSITE PIPES

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ABSTRACT

This paper presents an investigation carried out on a newly proposed procedure, the Ultimate Elastic Wall Stress (UEWS) test for qualification of filament wound glass fibre reinforced epoxy (GRE) pipe. The UEWS test, whilst not yet standardized, appears to offer an attractive alternative to existing procedures. It is envisaged that, with further study, the UEWS procedure may possibly form a premise for a full qualification program. This is provided that it can link the damage progression to the design life of the product as described in ASTM D2992 and ISO 14962. To date, a model based on Miner's law has been developed to illustrate the damage accumulation caused by fatigue cyclic and static loading in UEWS tests. The Miner's law model, gives a good account of the effect of cyclic and static loading in UEWS tests. Damage development can be directly linked to the progressive nucleation of matrix micro cracks using a crack growth model. It also has been shown that, cyclic loading dominates the UEWS test response compared to the static loading.

***Keywords**:* Ultimate Elastic Wall Stress (UEWS), hydrostatic design basis (HDB), matrix crack, cyclic and static loading.

1. INTRODUCTION

The preference of composite pipes to those traditional steel pipes has continued to rise as they are now becoming generally accepted due to their beneficial material properties, high strength to weight ratio and their superior corrosion and chemical resistance characteristics *[1-3]*. Fibreglass pipes most notably the filament wound glass fibre-reinforced epoxy (GRE) pipe is probably the most widely used composite pipes in oil and gas industry. Yet, as the use of GRE pipes becomes more common, evidently there is a need for design guidelines and universal standards for the GRE pipeline systems to be designed with assurance and generally accepted. Understanding and quantifying the factors that affect the burst strength, fatigue limitations and the failure modes will help the design engineer to come out with proper guidance that meets the long term performance of GRE pipes *[4, 5]*. The most important thing at this moment probably is to project the long term behaviour of these pipes (20-30 years) under complex loading based on the data recorded from short term failure tests.

In this work, an investigation has been carried out on a newly proposed procedure, the Ultimate elastic wall stress (UEWS) test for qualification of filament wound GRE pipe. Ultimate elastic wall stress (UEWS) test was chosen as the method for the short term test similar to that being practiced by FPI as their internal control and qualification process, supplemental to the standard qualification practice outlines by the ISO 14692 *[6]*. More often, the winding angle of ±55° are commonly encountered since this is the optimum angle for the internally pressurized pipe systems for $\sigma_H=2\sigma_A$ as suggested through a simple 'netting analysis' *[7-9]*. A model based on Miner's Law *[10]* has been developed to illustrate the damage accumulation caused by fatigue cyclic and static loading in UEWS tests. The work here also tried to link the damage development to the progressive nucleation of matrix micro cracks using a crack growth model.

2. QUALIFICATION AND TESTING PROCEDURES

ISO 14692 introduced in 2002 was the first international standard that linked the safety of an installed pipe system to the performance of individual components for GRE pipe systems. It is also the principal document that deals with the certification of fibreglass pipe. The standard describes the method used to establish the strength-regression data to obtain a hydrostatic design basis (HDB) or pressure design basis (PDB) for fibreglass pipes *[6]*. The standard delineated procedures in details for both; cyclic loading pressure and long term constant pressure loading in ASTM

D2992a and ASTM D2992b respectively *[11]*. It is also important to mention that, the discussion here and those set forth in ISO 14692 relate solely to GRE pipes that fail by weepage.

In the qualification process, the specimen loaded with ‘closed end’ condition where the hoop stress developed is twice the axial stress. With fibreglass pipe, it is usually found that, both cyclic and static behaviour exhibited a linear relationship between the logarithm of applied pressure and the logarithm of the lifetime (in cycles or time), as shown in the Figure 1. In order to demonstrate this, for both, constant pressure and cyclic loading, minimum of 18 points are required in order to establish an acceptable regression data, with at least one sample providing a point in excess of 10,000 hours and 15,000,000 cycles of internal pressure cycled at 25cycles/minutes, respectively. To allow some product variability and inconsistency in manufacturing that is bound to happen, it is necessary to compute the lower confidence limit (LCL) of the results. LCL denotes the line above which 97.5% of the newly determined regression data are predicted to lie as can be seen in Figure 1. The pressure rating for the pipe, known as the hydrostatic design basis (HDB) is then determined by extrapolating the LCL line to the design life which normally 20-50 years for offshore piping products. The HDB, combined with a number of other factors, is used to determine the qualification pressure in the pipe.

As mentioned before, ASTM D2992 outlines the procedures for carrying the hydrostatic pressure test under cyclic or long term static loading. Both types of failure can be described by the following power law expressions;

$$\sigma = HN_f^{-J} \tag{1}$$

for cyclic behaviour and

$$\sigma = Ft_f^{-G} \tag{2}$$

for static behaviour, where t_i is time in hours and N_i is the cycles to failure. These expressions can be re-arranged to give the time or number of cycles to failure, so:

$$t_f = \left(\frac{\sigma}{F}\right)^{-\frac{1}{G}} \tag{3}$$

for static fatigue conditions, and

$$N_f = \left(\frac{\sigma}{H}\right)^{-\frac{1}{J}} \tag{4}$$

for cyclic fatigue. The regression data obtained from this procedure provide important information that qualifies the product to be manufactured and defines the pressure rating to be used in pipe’s system design. It is also important when reconfirmation of the Hydrostatic Design Basis (HDB) is to be required. Reconfirmation of HDB is performed when there is a change to materials, manufacturing processes, construction or fitting design that might have an effect to the overall performance of the pipe. It would be expensive and time consuming to have the pipe subjected to full qualification program every time small changes were to be made. In this procedure, GRE pipe is subjected to the 1000 hours of hydrostatic pressure based on the 1,000 hour lower confidence limit (LCL) of the regression line acquired from ASTM D2992 (Figure 1). Survival of this test strongly implies that the pipe tested has the same design life or if not better than the originally qualified pipe.

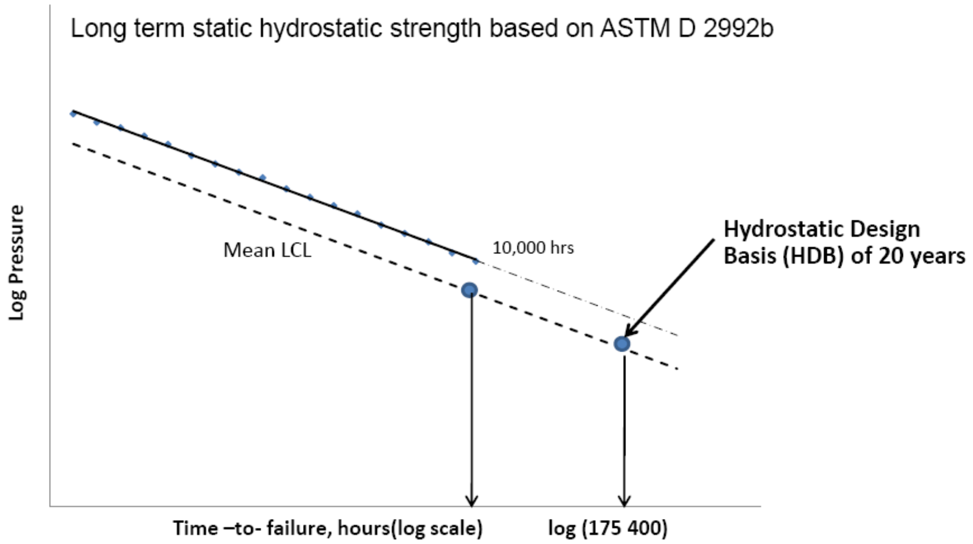

Figure 1 Long term static hydrostatic strength based on ASTM D 2992b showing the pressure at design lifetime of 20 years and the pressure at 1000 hours for reconfirmation test *[6]*

3. THE ULTIMATE ELASTIC WALL STRESS (UEWS) TEST

While the current procedure of qualifying GRE pipe based on regression analysis provide a very good prediction for long term behaviour of the pipe, manufacturers, driven by the need for fast and much simplified qualification process, have examined numbers of possible short term test; e.g. inter laminar shear stress (ILSS) test, flexural test and UEWS test. The principal of the UEWS was first investigated by Shell Research in 1968 *[12]*. UEWS has been defined as the maximum circumferential wall stress, resulting from internal hydrostatic pressure that produces an elastic deformation in any directions. There are very limited has been reported on the procedures. Hull *[13]* and Frost *[1]* both, have reported the UEWS test and observed that, through thickness matrix cracks is consistently associated with the non-linearity in stress strain response.

The intention of the UEWS test is to identify, by examining the stress-strain response, a stress level below which damage growth is either negligible or at least sufficiently low to prevent long term failure at the design life. Failure of GRE pipe will happen when debonding occurs between fibres and matrix interface. Once debonding takes place, there will be less surface area for proper stress distribution. This will lead to the development of stress concentration within the GRE system which, in turn, causes further debonding. Eventually, debonds coalesce to form a crack parallel to the fibres which later results in continuous weepage passages through the pipe wall. The onset of which the fibres-matrix interface starts to debond is used as the point to indicate the borderline between the permissible and non-permissible deformation allowed. This point is called Ultimate Elastic Wall Stress (UEWS).

In UEWS test, a specimen filled with water is loaded in a prescribed times versus pressure schedule which consists of cycle groups. Each group consists of ten one-minute cycles at pressure and one-minute cycles at no pressure, *[14]* as illustrated in Figure 2. The first Cyclic Test Pressure (CTP) shall be 10% of the pressure estimated pressure at UEWS. During the procedure, either hoop or axial strain is measured using gauges. The strain at the end of the first and the last cycle of each ten cycle group is measured and these values are plotted against hoop stress (or pressure). If the strain is completely reversible with deformation of less than 3%, the test is continued on the next cycle group with CTP further increased 10%. The UEWS point is considered to be exceeded when a difference in strain between the first and the tenth cycle is more than 3% or the stress strain relationship starts to deviate more than 3% of expected linear behaviour and becomes non-linear. The test was continued until one of the following criteria is met; weeping or failure of the pipe is observed or by further performing two cycle groups after the onset of non-linear behaviour of strain response. Two lines representing the linear and non-linear behaviour of the strains were plotted and the intersections of these stress-strain responses were then taken as the onset of failures for the GRE system.

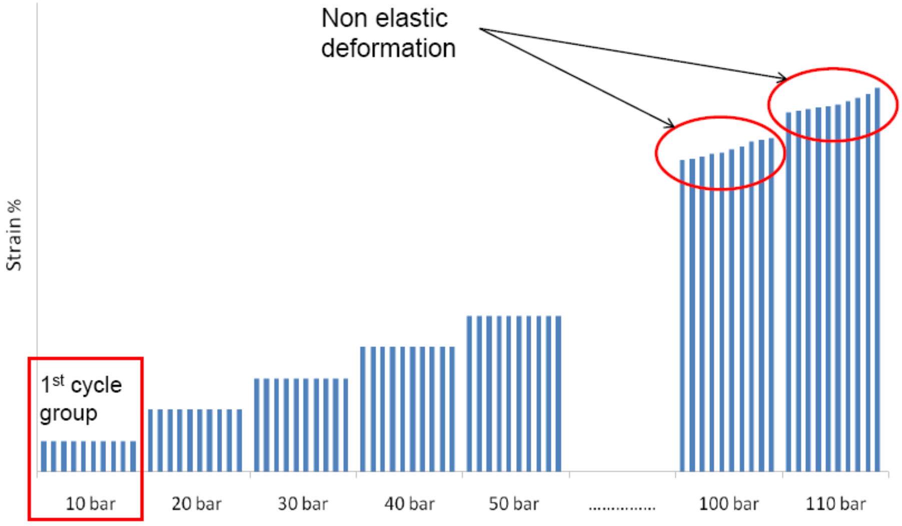

Figure 2 Pressure versus time during UEWS test *[14]*

4. MODELLING OF UEWS TEST USING MINER'S LAW

In order to model the damage accumulation being subjected to the GRE pipe during UEWS test procedure, which is thought to be governed by cyclic loading, a cumulative damage rule is certainly needed. Numbers of damage models have been employed to describe the damage development of composite materials in a recent decade *[15-17]*. For modelling UEWS procedure, a widely used, Miner's Law has been employed. Miner's Law *[10]*, which is an empirical law, is a generally accepted damage law in predicting the development of cyclic fatigue damage in metals. The law states that, for cyclic fatigue, failure occurs when,

$$\sum\frac{\sigma_i \Delta N_i}{N_{if}}=1 \tag{5}$$

Where N_{if} is the number of cycles to failure at stress level σ_i and ΔN_i is the number of cycles applied at each stress level σ_i of the fatigue cycle. It provides a method of summing the damage produced by fatigue cycles of different magnitude, which can be extended to model and sum the effects of other types of damage in composite structures. In the case of UEWS test where group cycles of different stress magnitudes are present, end of life is reached when;

$$\frac{\sigma_1 N_1}{N_{1f}}+\frac{\sigma_2 N_2}{N_{2f}}+\frac{\sigma_3 N_3}{N_{3f}}+\ldots..\frac{\sigma_i N_i}{N_{if}}+\ldots\ldots\ldots=\sum\frac{\sigma_i \Delta N_i}{N_{if}}=1 \tag{6}$$

This expression applies where N_1 stress cycles occur at stress σ_1; N_2 cycles occur at stress σ_2 and, in general, N_i cycles occur at stress, σ_i. N_{1f}, $N_{2f}\ldots N_{if}$ etc are the corresponding numbers of cycles that would cause failure in a cyclic fatigue test at a constant repeated stress of , σ_1, $\sigma_2\ldots\sigma_i$. etc. Using the derived expression, it is now possible to model the damage accumulation incurs during the cyclic loading of increased pressure in UEWS test. The same can now be generalized to enclose static as well as cyclic fatigue loading. The analogous static creep conditions can now be expressed as;

$$\sum\frac{\sigma_i \Delta t_i}{t_{cf}}=1 \tag{7}$$

Where t_{cf} is the creep failure at stress level σ_i and Δt_i is the time applied at each stress level σ_i. Hence, for UEWS test where static loading at different stress are present,

$$\frac{\sigma_1 t_1}{t_{1f}}+\frac{\sigma_2 t_2}{t_{2f}}+\frac{\sigma_3 t_3}{t_{3f}}+\ldots..\frac{\sigma_i t_i}{t_{cf}}+\ldots\ldots\ldots=\sum\frac{\sigma_i \Delta t_i}{t_{cf}}=1 \tag{8}$$

In this case, t_1, $t_2\ldots t_i$ etc. are the times at a specific stress level while, t_{1f}, $t_{2f}\ldots t_{cf}$ are the corresponding times to creep failure at constant values of these stresses. Limited literature was found reporting the combined effect of cyclic and static fatigue at the same time. One of few, Frost *[1]* concluded in his work, that both static and cyclic fatigues contribute to the matrix crack growth with one element usually seen to dominate the total damage induced. Frost then went on to proposed that, for a GRE system subjected to combined static and cyclic loading, similar to the UEWS test, the failure is predicted to occur when;

$$\sum\frac{\sigma_i \Delta t_i}{t_{cf}}+\sum\frac{\sigma_i \Delta N_i}{N_{if}}=1 \tag{9}$$

It is very interesting to find out if the damage accumulation model derived above can be related to the design lifetime of GRE pipe obtained from the regression based procedure as described before. Rearranging equation (3) and (4) and integrating them with equation (9), allow the failure state to be predicted for loading histories containing both static and fatigue loading. Thus, the total Miner's Law sum is now given as the following;

$$\sum\left(\frac{\sigma_i}{F}\right)^{\frac{1}{G}} t_i+\sum\left(\frac{\sigma_i}{H}\right)^{\frac{1}{J}} N_i=1 \tag{10}$$

Since UEWS test involves the application of groups of 10 one minute cycle with pressure and one minute cycle without pressure, simplified approach above can be used to predict design life of GRE pipes. In UEWS test, with a stress increment, $\Delta\sigma$, the usual conditions of a cyclic loading period one minute and groups of 10 cycles, this is given by;

$$\frac{10}{60}F^{-\frac{1}{G}}\left(\sigma^{\frac{1}{G}}+(2\sigma)^{\frac{1}{G}}+(3\sigma)^{\frac{1}{G}}+\ldots\ldots\right)+10H^{-\frac{1}{J}}\left(\sigma^{\frac{1}{J}}+(2\sigma)^{\frac{1}{J}}+(3\sigma)^{\frac{1}{J}}+\ldots\ldots\right)=\Phi \tag{11}$$

where the first term represents the static loading effect and the second term denotes the cyclic fatigue. Using the constants value acquired from regression analysis, as listed in Table 1 for FPI fibreglass product; damage accumulation based on the modified Miner's Law can be computed for each stress level during the UEWS test. Figure 3 shows the damage accumulation from the static and cyclic loadings of UEWS test.

As can be seen in Figure 3, damage accumulation due to cyclic element during UEWS test clearly predominate the contribution from the static loading. This suggests that, matrix micro cracks development in GRE pipe was governed by cyclic loading as more time would be required for static condition to cause the same damage accumulation as the cyclic element. Bourne in mind, however, in UEWS test, the static loading applied, have been very little, in effect, as it is only applied for one minute over ten group cycles whilst the regression based procedure requires more than a year of constant pressure loading to complete. On the positive side, this approach enables the whole test to be completed within a day. Still, since the UEWS has been shown to be governed by cyclic loading, in order for the procedure to be employed for qualification purposes, additional information is needed regarding the relationship or equivalence between the damage caused by the cyclic loading and that produced statically.

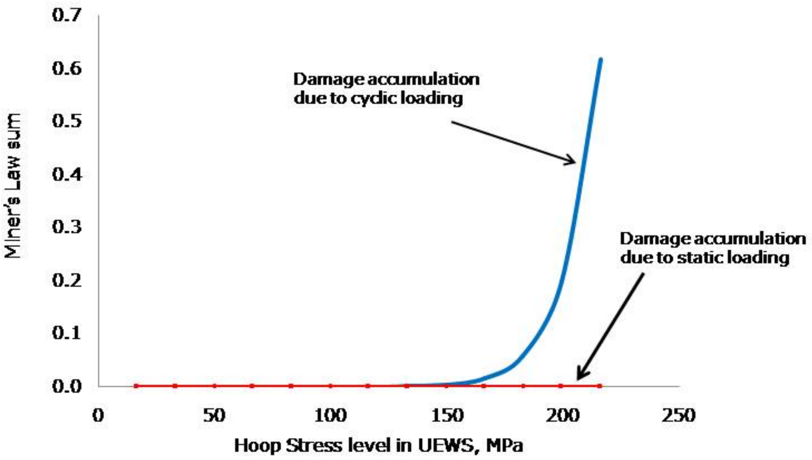

Figure 3 Miner's Law sum at each hoop stress level showing static and cyclic element in UEWS test.

In order to predict the lifetime pressure rating for the GRE pipe, the effect crack density must be considered in the constitutive law which defines the stress strain relationship. In addition, a growth damage law also needed to relate the stiffness reduction to the loading history. The parameter normally used to define the damage state is the crack density, $\boldsymbol{\rho}$, measured in the ply transverse direction. $\boldsymbol{\rho}$ is dimensionless, being defined as the ratio between ply thickness and average distance between micro cracks *[18]*. This gives a means of taking into account the well-known effect of ply thickness on crack growth. It is assumed that weepage takes place at a critical value of crack density, $\boldsymbol{\rho}$ weepage, and that this value is the same despite how the weepage state is reached (i.e. by different combinations of static and cyclic loading or different combinations of internal pressure and axial load).

As mentioned before, GRE pipe failure is always governed by the cracks propagating through the matrix phase. Once initiated, the matrix cracking grows expeditiously in the direction of the fibre, since there is fairly little crack growth resistance to slow down the crack propagation. Therefore, the major factor governing the damage development in GRE pipes is in fact the crack initiation rather than crack growth. Frost and Cervenka *[1]* suggested a damage growth model for GRE pipe using a relationship analogous to the Paris Law used for crack growth in metals. The modified Paris Law describes the rate of change of crack density, rather than the increase of a single crack so, for the matter of cyclic fatigue;

$$\frac{d\rho}{dN} = A\sigma^n \tag{12}$$

where *A* is the proportionality constant, *N* is the number of cycles and *n* is the experimentally determined exponent. The above expression can then be generalised to consider the effects of combined static loading and cyclic loading, hence;

$$d\rho = A\sigma^n dt + B\sigma^m dN \tag{13}$$

where *t* is the time to failure for static loading. Interestingly, the form of crack growth law in equation (13) is similar and can be treated as analogous to the Miner's Law sum in equation (10). This can now be used to relate the crack growth to the damage accumulation rule previously derived from modified Miner's Law. Comparing the two power law equation, *m* and *n* exponent constants in equation (13) are now equivalent to the 1/J and 1/G in equation (10). It is now possible to model the stress strain response in the UEWS test from the degradation of elastic properties caused by the progressive matrix cracking. By using the results from Gudmundson and Zhang, the dimensionless change in the 'hydrostatic/axial modulus' (the hoop stress divided by the axial strain) and the 'hydrostatic/ hoop modulus' (the hoop stress divided by the hoop strain) with increasing crack density is calculated. Provided the critical value of crack density of which weepage is expected to occur is taken to be 0.4, both quantities can be described by the following linear approximations;

$$\frac{E_A^{UEWS}}{E_{A_0}^{UEWS}} = 1 - 1.66\rho \quad \text{and} \quad \frac{E_H^{UEWS}}{E_{H_0}^{UEWS}} = 1 - 0.16\rho \tag{14}$$

To relate the crack density growth to the damage accumulation law by Miner's law in the UEWS test, equation (11) can now be expressed in the following from;

$$\Phi = k\rho \tag{15}$$

Hence, substituting equation (15) into equation (14), provides the expression for elastic change, the expression for elastic change which now can be directly related to the Miner's Law sum, so that;

$$\frac{E_A^{UEWS}}{E_{A_0}^{UEWS}} = 1 - 1.66\frac{\Phi}{k} \tag{16}$$

For a *k* value of 2.5, a Miner's Law-based simulation of stress strain response in UEWS tests is plotted as shown in Figure 4. The result reveals that the proposed model successfully offers the possibility of modeling the reduction in the elastic properties during UEWS tests with regards to both, crack growth and Miner's Law. Provided the crack density is less than about 0.4, the changes in the elastic constants can be described by linear approximations. It should therefore be possible to use the Miner's Law Sum to deduce the variation in elastic constants during the design life or indeed during a UEWS test.

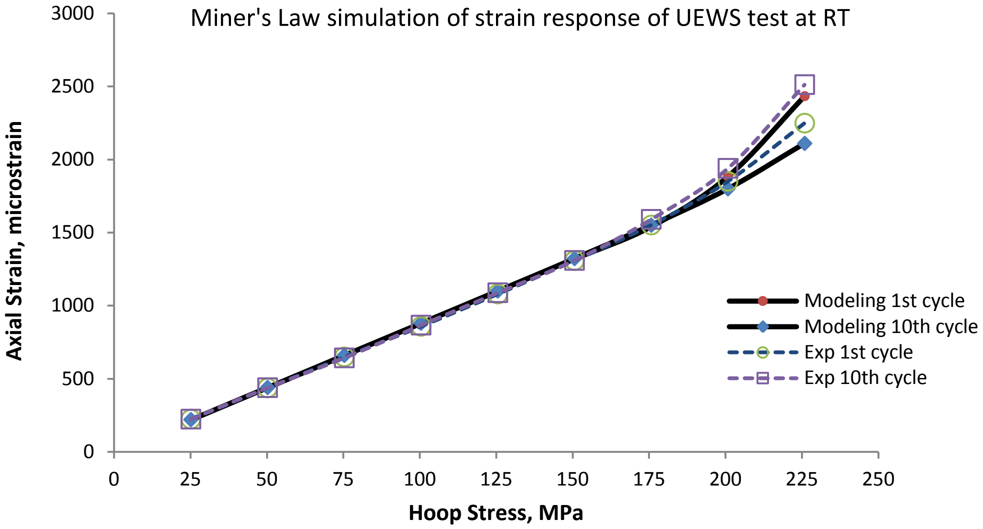

Figure 4 Miner's law modelling of UEWS stress-strain response for hydrostatic case with 2:1 hoop to axial loading at RT.

4. CONCLUSION

The existing procedure of qualifying and reconfirming GRE pipe has been discussed. It is acknowledged that, in order for UEWS test to be considered for the full qualification program, an investigated link between UEWS values and the statistically determined design life or HDB of pipes needs to be established. It is also been shown that UEWS test is practically a cyclic fatigue loading from the damage accumulation model developed based on the Miner's Law. The effect of static fatigue is almost negligible for the case of UEWS and additional information is needed to ensure the equivalency of the damage caused by loading cyclically and statically. By employing a crack growth model similar to Paris Law, damage development was successfully linked to the progressive initiation of matrix micro cracks. The result shows that the suggested model offers the prospect of modelling the reduction in the elastic properties during UEWS test.

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