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# A Review of Multi-Axial Fatigue Tests

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# A Review of Multi-Axial Fatigue Tests

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**Abstract.** Nowadays, estimating the fatigue life of almost any industrial component under multi-axial loads is still a very complicated issue. In this paper, models of multi-axial fatigue for various loading conditions depend on damage parameters conditions shown with a comprehensive review of the multi-axial fatigue machines designed to provide proportional and non-proportional combined loading conditions in the laboratory and corresponding models developed to predict specimens fatigue life. A brief of experimental multi-axial fatigue results reported by previous studies is also presented. Especially, the focus here is on combined bending-torsion and axial-torsion conditions. Such a study allows for a better understanding of the effect of the loading path on material fatigue behaviour during their real operations. Also, predicting fatigue life accurately under non-proportional complex loads will give clear data about when this component is a failure during a real process.
**Keywords.** Fatigue, Multi-axial fatigue, Proportional and nonproportional loading.

## 1. Introduction

Different mechanical components such as machine components, wind turbine, driveshafts, and others are subject to repeated multi-axial load forces. This results in complex stress and strain distributions at the critical plane of the specimen. So, by using traditional analytical and numerical techniques employing an equivalent uniaxial load case, the fatigue of these components will be analyzed [1]. Multi-axial fatigue is an accident affects the components in several industries, including automotive and aerospace. Also, multi-axial fatigue is important in oil drilling companies because nonproportional loads subjecting on drilling pipe during oil drilling prosses components are subjected to multi-axis stress facing several challenges in optimizing appropriate parameters and methods to estimate fatigue life. Accurate understanding and prediction of the tensile life for components in multi-axial stress is essential for engineers. At the same time, proper designs are created to withstand the design required for life without being too conservative. The methods and criteria for developing multi-axial fatigue present several problems that must be overcome. Empirically, providing multi-axis stress for test components is challenging due to the challenging nature of stress measurement under multi-axis load and the prohibitive costs. At present, only a few universities and companies have the capabilities required to take an accurate multi-axis stress test. Because of this condition, the multi-axial stress analyses on materials are usually torsional or uniaxial, by an extrapolation of the multi-axial fatigue load conditions [2]. Experimental observations indicated a critical level where nucleation of the crack fatigue tending to happen at preferred levels or directions in materials. In the past few decades, critical plane models have been an extension to estimate the fatigue life of materials and cover this phenomenon [3][4][5]. This paper is not intended to review research for a multi-axial fatigue machine, but rather a review of tests results for different materials tested by these devices and a discussion of their results. Also, this paper includes the critical multi-axial fatigue models used to predict fatigue life for nonproportional loading.

## 2. Non-Proportional versus Proportional

Two different parts of combined loading classified are proportional and nonproportional loading. So, when ratios between the principal stresses remaining constant in a fixed orientation during the loading cycle, this is called proportional loading. Therefore, in this type of loading, the maximum and minimum principal stresses get their path at the same moment, as shown in (Figure **1** a and b). In contrast, the nonproportional loading is shown in (Figure **1** c and d) [5-7]. In laboratory, mostly when the two different loadings of the component test multi-axial fatigue specimens, it will be time-consuming and expensive. For instance, Morrow in 1989 [8] employed a tension-torsion machine to investigate the behaviour of Inconel 718 under proportional and non-proportional loading.

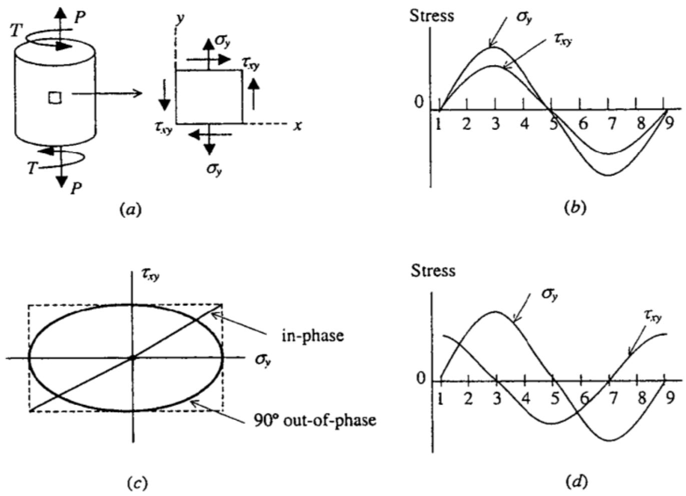



**Figure** 1. Diagram of proportional and nonproportional loading. (a) Axial-torsion loading. (b) In-phase axial loading. (c) Loading path for proportional and nonproportional cases. (d) Out-of-phase axial loading [5].

## 3. Experimental machine test

The stress-strain condition becomes complex when non-proportionate loadings with variable quantity are applied. Using an experimental test is essential to obtain a better knowledge of fatigue under non-proportionate conditions. Using fatigue test devices are able to control realistic multi-axis loading conditions and apply them to test samples. [9] [10]. Previous research showed that the non-axial data could not be applied to realistic conditions of complex multi-axial fatigue major axis movement and non-proportional loading. [11][12][13][14]. Several criteria for fatigue have been presented, but none of them has been generally accepted [14][13]. In this area, a few experimental works have been done due to the need for suitable multi-axial fatigue testing rigs. Reliable stress test abilities are required for multi-axial stress study. The first ideas to combine multi-axial fatigue loading utilizing hydraulic actuators. This method was utilized because it replicates one of the most significant multi-axial loading conditions establish in components and structures [15][16]. Stoychev and Stefanov [17] discussed two different experimental technical ways to apply multi-axial combined torsion and rotating bending nonproportional loading, indicating that this technology has always been important and actual for the real rotating machine of the fatigue life. The first technical way was regular to fix specimen between an electromotor and a hydraulic brake then subjecting it to rotating bending with constant torsion as shown in Figure 2. The statically indefinite system with two rotating shafts were interlocked together by mutually twisted gears. The motor was used to drive these shafts and cover the power waste. In this system, the specimen in the anterior shaft (conduction) will support Figure 2 and keep thread inserting (15) and conical inserting (17). That fitting defines a sample and contact column to transmit the bending load. The specimen is bent (Cardin 13 joints). The second column of the system is used to transfer the torsion to the sample by four rollers connected between two columns, and a flange (28) constantly attached to the right secondary shaft, instead of the pulley (29) [17].

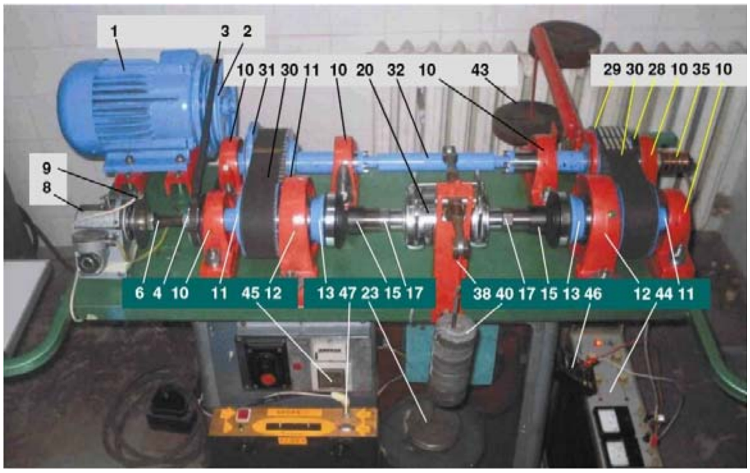



**Figure 2.** multi-axial fatigue testing machine [17].

The second technical way has more advantage than the first, where the specimen is fixed, and the bending plane is made rotating as shown in Figure 3. Furthermore, it has a small size compared with other machines. The sample is put in a hollow shaft (8) of a normal multi-speed electric motor.

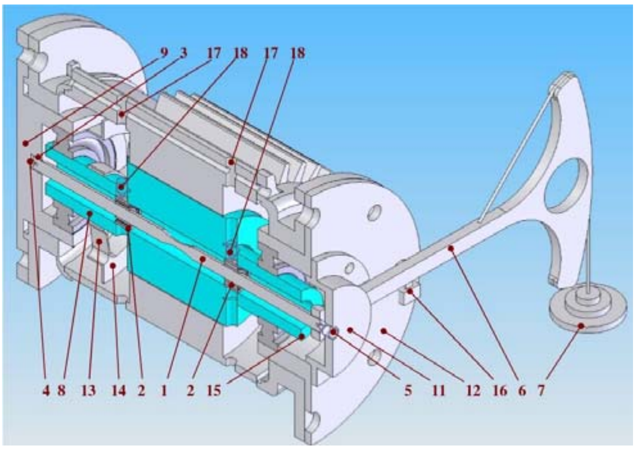
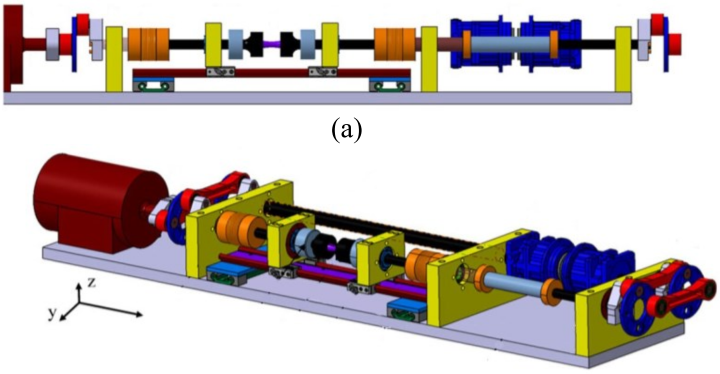



**Figure 3.** Multi-axial fatigue device [17].

Van Hooreweder and Moens [18] designed and simulated a multi-axial fatigue test rig for subjecting specimens to bending and torsional stresses. The advantage of this machine is that it can control 19 load conditions individually. The theory allows for a wide range of detailed test conditions to reality life applications bending and torsion. The design of the test rig is shown in Figure 4



(a)

(b)

**Figure 4.** Design of the test rig (a) side view and (b) isometric view [18]

There is no need to mention the year, first name or any detail in the citations. The reader can see such details in the references. Such details could be helpful in history or sociology studies. Papasidero, et al [19] used a hydraulic torsion axial load frame and an internal compression load frame for all experiments common tensile torsional fracture tests presented on a high strength isotropic steel initially. This device shown in Figure 5 was used to test a multi-axial for a ductile tube specimen with a gauge segment filled to a uniform thickness.

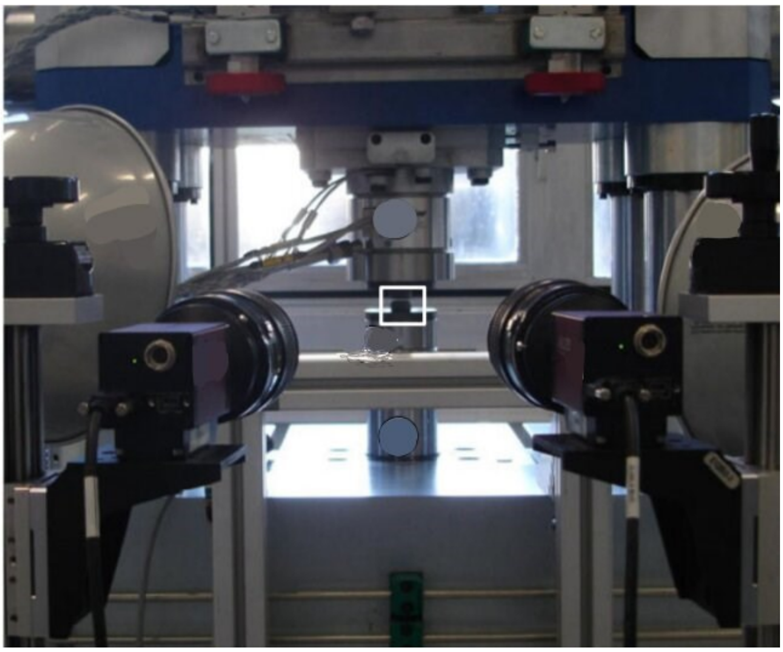


**Figure 5.** Photograph of the experimental setup [19].

Mechanical College al K. N. Toosi University of Technology in 2010 [20] designed and manufactured a multi-axial fatigue device. A full-size drill pipe specimen was used in this machine, subjected to rotating bending with constant torsion proportional load. This machine was very large to take place for a full-size drill pipe specimen, whose length was 9000mm. An electric motor and cams-disc ware was employed to subject combined bending and torsional loading, as shown in Figure 6). The vertical force was subjected to the top of cams-disc, as shown in Figure 6 a to produce a bending load. At the same time, the proportional torsion load was generated by horizontal springs force on the side of cam-disc Figure 6 b). The disadvantage of this machine was a large size and heavyweight, which limits the variety of the tests in this machine.


**Figure 6.** Experimental setup (A) bending cams (B) Torsion cams (C) cams-disc and flywheel work mechanism [20].

## 4. Multi-axial fatigue life prediction models

In the mid-twentieth century, several fatigue models have been improved to estimate the multi-axial fatigue life. Equivalent stress, stress and energy models, were explained quickly, then the critical plane models obtained extra importance. The first three methods are at most dependent on crack nucleation.

### *4.1. Equivalent stress models*

Equivalent stress models are commonly developed as additions of classic static yield theories, with parameters that have been determined to apply to uniaxial fatigue approaches such as Gerber's model [21] or Goodman's model [22]. Under high cycle stress (HCF) situations, all equivalent stress models are usually utilized because crack nucleation spends most of the fatigue life. Two models are often applied; the maximum shear stress theory (Tresca) and octahedral shear stress theory (von Mises). The principal purpose is to decrease multi-axial stress instances into parameters that can be done with uniaxial fatigue models [5]. The first to normally be computed for equivalent stress models is the equivalent stress amplitude. The following two equations illustrated are Tresca and von Mises, respectively.

$$S_{qa} = S_{a1} - S_{a3} \quad (1)$$

$$S_{qa} = \frac{1}{\sqrt{2}}\sqrt{(S_{a1}-S_{a2})^2+(S_{a2}-S_{a3})^2+(S_{a1}-S_{a3})^2} \quad (2)$$

$S_{qa}$ is the equivalent stress amplitude, and $S_{a1}$ , $S_{a2}$ , $S_{a3}$ the principal stress amplitudes the maximum base stress approach showed a good result similarity with brittle materials than the octahedral shear stress approach [5].

### *4.2. Equivalent strain models*

Equivalent stress models were explained for low cycle stress (LCF) states. The approach to equivalent stress models is similar to equivalent stress models, but the parameters are used in some stress and life equations. The equivalent stress amplitude parameter that are usually found take theories of maximum shear stress, or the octahedral shear stress theory. Equations for the theory of maximum shear stress and the octahedral shear stress theory below are related to equivalent stress amplitude parts. The maximal main stress theory is usually applied to brittle materials, while the octahedral shear stress theory is for ductile materials. [5].

$$\varepsilon_{qa} = \frac{\varepsilon_{a1} - \varepsilon_{a3}}{1+\upsilon} \tag{3}$$

$$\varepsilon_{qa} = \frac{\sqrt{(\varepsilon_{a1} - \varepsilon_{a2})^2 + (\varepsilon_{a2} - \varepsilon_{a3})^2 + (\varepsilon_{a1} - \varepsilon_{a3})^2}}{\sqrt{2}(1+\upsilon)} \tag{4}$$

$$\varepsilon_{qa} = \frac{\sqrt{(\varepsilon_{a1} - \varepsilon_{a2})^2 + (\varepsilon_{a2} - \varepsilon_{a3})^2 + (\varepsilon_{a1} - \varepsilon_{a3})^2}}{\sqrt{2}(1+\upsilon)} \tag{5}$$

$\varepsilon_{qa}$ is the equivalent strain amplitude, $\varepsilon_{a1}, \varepsilon_{a2}, \varepsilon_{a3}$ principal strain amplitudes. After computing the equivalent stress amplitude, will replacing by the term stress amplitude, in the stress-life equation.

$$\varepsilon_{qa} = \frac{\sigma'_f}{E}(2N_f)^b + \varepsilon'_f(2N_f)^c \tag{6}$$

where $\sigma'_f$ the fatigue strength coefficient, *E* the modulus of elasticity, $2N_f$ the number of reversals, *b* the fatigue strength exponent, $\varepsilon'_f$ the fatigue coefficient, and *c* the fatigue exponent.

The equivalent stress amplitude parameter is utilized in agreement with others such as the Smith Watson Topper (SWT) parameter. [23]. However, if great amount of plasticity occurs, stress relaxation can be introduced, which can add a fatigue life benefit to the component. In relation to equivalent stress models, equivalent stress models are preferable for proportional loading situations and are not capable of dealing with non-proportional loading. In order to deal with non-proportional loading situations, various models must be considered [5].

### *4.3. Energy models*

Energy models are similar to equivalent stress and strain models, where stress and strain are employed to find a standard parameter for each load cycle to calculate the fatigue life [24]. The fatigue lifetime is calculated by summing the stress damage for each cycle and correlating this damage with other parameters Garud models [25] attempted to apply the effects of the deceleration loop to multi-axial fatigue. The plastic work is examined for each cycle by dividing the work to periods. The plastic action is then summed up in each cycle then used to determine the fatigue lifetime. Eq **(2)** calculates the plastic work per cycle.

$$\Delta W_c = \int_{cycle} \sigma_{ij} d\varepsilon_{ij}^p = \sum\nolimits_{cycle} \Delta W_p = f(N) \tag{7}$$

$\Delta W_c$ the total plastic work per cycle, $\sigma_{ij}$ the stress tensor, $\varepsilon_{ij}^p$ the plastic strain tensor, and $\Delta W_p$ the total plastic work per increment. The whole plastic work per cycle is explained to estimate fatigue life. This approach estimates the life of multi-axial fatigue showing hope of collecting material data [25]. The plastic work of each cycle is a scalar amount, which does not significantly present a physical meaning to the start of the crack. This model can be suitable for both proportional and non-proportional loading situations, but in the cases of HCF, the plastic work flowing per cycle is either very low or non-existent, making this approach extremely hard to utilize for estimating fatigue life. Energy methods were not generally accepted due to the numerical nature of the models, and the lack of physical similarity. These methods are used to calculate non-proportional load; however, mathematically, this will be difficult, especially in the complex load cycle [5].

### *4.4. Critical plane models*

The third major type of multi-axial are critical planar models which are stress criteria explained over the past century to predict crack nucleation. Experimental data showed that fatigue notch is generally plotted in directions named critical planes. These planes are usually the shear stress/strain or normal stress/strain amplitude at maximum, depending on the material and the loading cycle. Some models are based primarily on stress-related parts, but the others on strain-related. Critical level methods usually depend on maximum shear level or maximum baseline failure mode, which can be categorized as stress-based, stress-based, stress-based or energy-based models [5]. Overall, the critical planar models have been shown to be effective in estimating the life of fatigue. Several models have been presented in the last years, the most popular are examined in this section. The disadvantage of the critical level models is the additional computational time explained, such as the fit of the curve to the constants in a few models. [5]. The first model was suggested by Findley [26]. Findley explained a parameter established from the shear stress amplitude and normal stress, with the critical plane standing at the maximized of parameter. Eq. 8 shows the Findley model:

$$[\frac{\Delta\tau}{2}+k\sigma_n]_{\max}=f(N_f) \tag{8}$$

where $\Delta\tau$ the shear stress range, $\sigma_n$ the normal stress, $k$ a material calculated constant, and $f(N_f)$ a term that is a function of the fatigue life, calculated at the critical level when the parameter is greater. The Findley parameter showed an assuring data association in cases of HCF [6] and is usually use for such cases. Brown and Miller [11] explained crack beginning in planes of maximum shear stress, and concluded that this shear stress and normal stress were responsible for the initiation of cracks at the critical level. The Brown-Miller parameter is shown in Eq 9.

$$\frac{\Delta\gamma_{\max}}{2}+s\Delta\varepsilon_n=f(N_f) \tag{9}$$

where $\Delta\gamma_{\max}$ the maximum shear strain range on the critical plane, $\Delta\varepsilon_n$ the normal strain on the critical plane and ***s*** a material constant. This criterion is usually employed for LCF states considering the terms strain. Several critical plane models were introduced, with the aforementioned models generally accepted. Critical plane models estimate multi-axial fatigue, given that they approach physical measurements of crack nucleation. Critical level models are also utilized for uniaxial loading and torsion states. Many uniaxial loading conditions naturally use multi-axial stresses of materials, especially when the notch is present [5].

## 5. Analysis of multi-axial fatigue testing results

There are a lot of experimental studies on multi-axial fatigue testing, but just a few articles explained details about how the test was taken and what the machine looked like. So, in this part of the paper, some of the experimental results will be shown and discussed. Stoychev and Stefanov [17] illustrated an experimental multi-axial fatigue life for Hardened 45 steel material under combined rotating bending and constant torsion loading. This test showed an interesting effect for increasing fatigue life during applying constant torsion force to the specimen when the specimen under a rotating bending. This causes the ratio of shear stress to bend stress still small. Additionally, by utilizign fatigue machine in Figure 2, a correct experimental data could not be provided for trying to make $\tau/\sigma_a$ greater than 0,3. Because other technical solution in Figure 3 was suggested. Also, Stoychev, B. I., and S. H. Stefanov used an IDD method (Integration of Damage Differentials) and compared the result with the experimental data as shown in Figure 7. The results show the effect of increasing $\tau/\sigma_a$ ratio on increasing fatigue life. In the case of constant torsion that is summed to the rotational bending with $\tau/\sigma_a$ up to 0,3 in the experimental test showed how life increase was significantly affected at higher $\sigma_a$ levels. At a $\sigma_a$ level, the effect is adjusted to keep the fatigue limit of the same despite additional twisting.

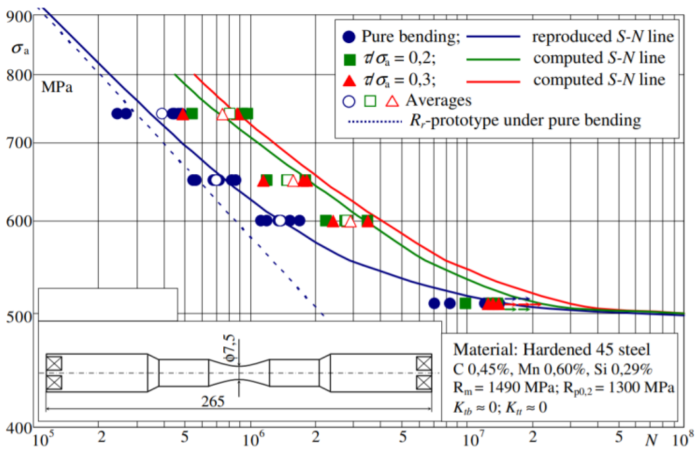
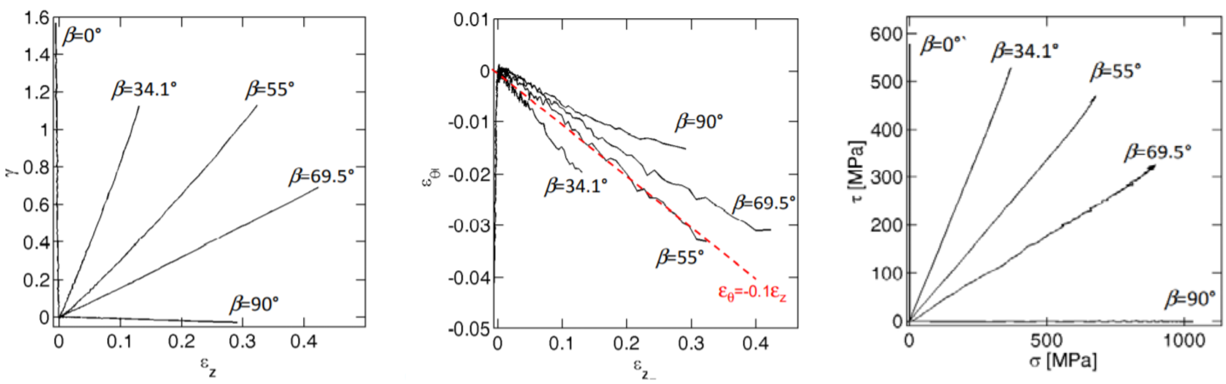



**Figure 7.** Experimental lives and IDD verification [17].

Jessica Papasidero and Veronique Doquet used a Hosford–Coulomb damage indicator model to explain the effect of stress condition on the non-proportional and proportional ductile fracture for tension - torsion loading. Then they used the machine shown in Figure 5 to test a tubular specimen. A hydraulic axial / torsion loading and internal pressure were applied to a 35mm-hole specimen including a measuring section of uniform thickness made from high strength steel 36NiCrMo16 [19]. Also, Jessica Papasidero used aluminium 2024-T351 specimen under tension - torsion loading [27]. Throughout the experiment test, method one: Surface-strain Based Estimates and method two: Full FEA analysis were supposed to measure the loading paths to fracture. Finally, a hybrid system testing, numerical plane was identified and used to calculate the parameters of the Hosford-Coulomb (HC) fracture initiation model. Moreover, finite element simulations were implemented for experiment tests to predict stress and strains away from the sample surface. The results of these test showed the effect of loading paths, as shown in Figure 8. The maximum shear strain under torsion and a maximum axial strain were observed. The diagram of growth the circumferential strain (Figure 8 b) indicates that the theory of plane strain conditions along the perimeter is not perfect. As in the stereo DIC measurement, the magnitude of the circumferential strain (contraction) was about 10% of the axial strain. The loading paths in terms of true average stress and axial stresses (Figure 8 c) were almost linear and the immediate result kept the loading angle β constant throughout the load.




(a) (b) (c)

**Figure 8.** (a) nominal shear vs axial strain loading, (b) nominal peripheral and axial strain loading, (c) means true shear versus true normal stress loading [19].

Berto et al. [28] used experimental tests for a large number of specimens made of Ti-6A1- 4V carried out under combined, in-phase and out-of-phase loads of tension and torsion as shown in Figure 9. In this test, an AMTS hydraulic machine with axial load cell and a torsion load cell Nm was utilized. Also, a function for the applied load was conducted load control at a frequency in range of 10 and 15 Hz. Thus, the cylindrical specimens in this work were weakened by circumferential notches such as plain and V-notched samples. Overall, a large number of fatigue data have been shown and compared with non-notch data and V-notched specimens under pure tension and pure torsion loading. Then, by the local strain energy density, the synthesis made specimens data cause a quite limited scatter band for all types of loading independent of the load ratio and phase.

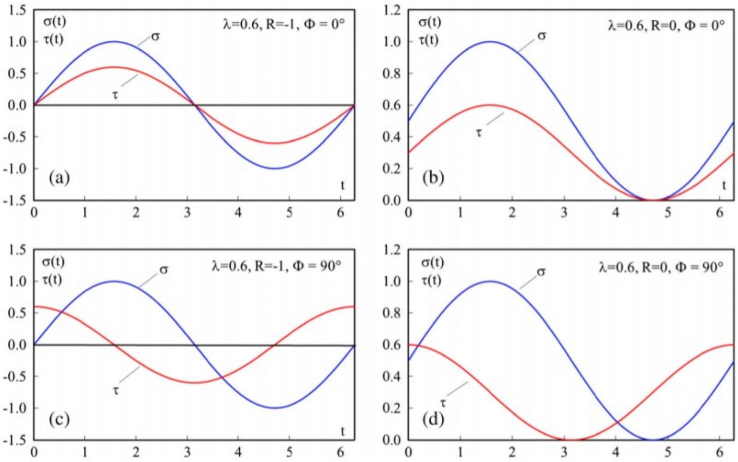



**Figure 9**. Wave forms for all one of multi-axial loading pattern. (a) (b) in phase, and (c) (d) out-of-phase [28].

Blazya et al. [29] proposed a statistical yield/failure surface model based on the application of effective stress. The model can estimate the average mean initial yield/failure stress and normal dispersion for multi-axis loading conditions. This simple mechanical model can produce the fracture statistics of brittle foams from knowing the cell size distribution. In this work, more than 80 specimens with sizes were tested under combined tension/compression-torsion. The non-proportionate loading path contains a tensile test followed by twisting, which maintains the axial stress constantly. In the proportionate loading path, the shear stress and axial stress develop a direct line in the stress space. In conclusion, the experimental results were acceptable with the predictions of the statistical model. Also, this model can account for the scatter details of this surface. Wu et al. [30] analyzed the multi-axial fatigue behavior of titanium (TC4) alloys and found that multi-axial fatigue models suitable for estimating the fatigue life of these alloys. Six multi-axial fatigue models were evaluated in this work. So, all fatigue tests were performed, including axial, torsion, in-phase, out-of-phase, and out-of-phase, under fully inverted sine waveforms. As a result, additional hardening for specimen was examined under out-of-phase loading conditions. The non-proportional loading paths had a small effect on fatigue damage in the short life area. The results proved the WHS parameter is suitable for alloy material. Also, the additional hardening has a smaller effect on fatigue damage in the region of long life, the advantage that the FS parameter can consider for additional hardening is not shown for TC4 titanium. Wui et al. [30] developed and implemented method to estimate the fatigue life for (TC4) material alloy under variable multi-axial loads. This multi-axial fatigue variable was applied based on Wu-Hu-Song method, and rain flow cycle calculation and Miner-Palmgren used in this method. A servo-hydraulic MTS Model 809 axial–torsion testing system has been used to apply a suitable load on tubular specimens. The load paths were grouped into four sections; (i) the tensile load, located at different positions for a single periodic torsion load, (ii) the tension loading quantity is variable, and the torsional loading quantity is constant, (iii) the tension loading quantity is constant, and the torsional loading quantity is variable. (iv) the amplitude of the tension and torsional load is both variables. Finally, the predictability of fatigue life of the presented method was verified against the TC4 alloy test data. Then, the results showed the introduced method is correct for estimating the fatigue life of TC4 alloys under multi-axial loading with variable amplitude. Ying-Yu Wang and Wei-Xing Yao [31] studied fatigue crack nucleation angle on two kinds of tube specimens; one is smooth, the other is grooved under multi-axial loading. The experimental test included various metallic material (LY12CZ aluminium, 6061 aluminium, and 1045 steel) under proportional and non-proportional loading. In this work, the maximum shear strain plane and the maximum fatigue damage plane were used to define a critical plane. Then, the estimation ability of the introduced parameter and the common multi-axial fatigue model recommended by Kandil, Brown and Miller are examined against experimental data for materials tests. In the end, the Kandil, Brown and Miller (KBM) parameter demonstrated that the new critical level criterion gives a good similarity with the multi-axial fatigue life of both proportional and nonproportional loading conditions for separate materials stress data. Xiong and Yanyao Jiang [32] studied a periodic deformation and fatigue life of an AZ31B Mg notched shape thin-walled hole by using a test specimen under combined axial torsion loading. Also, using two critical plane multi-axial fatigue models, the modified Smith–Watson–Topper (SWT) model and the Jiang multi-axial fatigue model. Where The modified Smith, Watson, and Topper (SWT) parameter were originally developed to consider the mean stress effect under uniaxial loading, and the criterion was extended to multi-axial fatigue by Socie with a critical plane and Jiang fatigue criterion. Finally, the results of the experimental test were compared with the model's output when the loading paths were employed in four full reversed ways: tension-compression, pure torsion, proportional axial-torsion, and 90◦ out-of-phase non-proportional axial torsions. So, by identical equivalent strain magnitudes, non-proportional loading produced the minimum fatigue life, proportional axial, torsional load and tensile stress load resulted in similar life and longer stress period. The modified Smith, Watson and Topper stress model and the multi-axial fatigue standard for the critical Jiang plane can give reasonable estimations of material stress life under combined axial torsion loading paths.

Bernasconi et al. [33] investigated the multi-axial fatigue behavior for a steel R7T, where the steel R7T was used to make high-speed solid rail wheels. The experiments of biaxial fatigue tests were applied to specimens extracted from rim of railway wheels, which were applied under an alternating torsion and spring pressure for $90^o$ phase-shift. Also, they applied Dang Van's criterion and Liu and Papadopoulos criteria to get role of normal stress in fatigue crack intention and the impact of static normal stresses on fatigue limit. Finally, increasing the absolute value of the negative axial load is to reduce permissible of shear stress amplitude resulting from the torsional load. As well, variations between the estimations of Liu and Papadopoulos model were observed at considering the effect of residual stresses.

Berto, Razavi, and Ayatollahi [34] summarized more than 120 new fatigue data by using a circumferentially V-notched (V-notch opening angle of 90 ) specimens and semicircular notched made of 40CrMoV13.9. The specimens were tested by an MTS 809 hydraulic biaxial machine for both in-phase and out-of-phase. Then, the value of the strain energy density (SED) was determined numerically by utilizing the FE code ANSYS 12.0 for both V-notched and semicircular notched samples. Finally, all fatigue data were shown in terms of nominal stress amplitudes firstly, then re-analyzed in terms of the mean value of the strain energy density estimated on a semicircular sector of specific size surrounding the notch tip. Matthew E. Alan R. et al. [35] analyzed uniaxial and multi-axial fatigue for (Ti–6Al–4V) and three other material, namely, Rene'88DT, Rene'104 and Direct Age 718, presented within the framework of a critical-plane methodology. Biaxial axial/torsion tests on the materials were conducted in strain control utilizing a solid smooth specimen, wherever specimens load path cycles are designed to give critical information for damage parameter development as well as to implement a certain level of stimulation the multi-axial loads found in gas turbine component. Moreover, critical level approaches based on strain-stress, which take into account the direction of the level at which the crack is intentional, have shown better benefit in associating experimental results for a variety of loading paths compared to equivalent stress models. Finally, a majority of these measured on the plane of maximum shear-stress amplitude were given to provide a good correlation of uniaxial and biaxial fatigue data (Ti–6Al–4V) and three other material, namely, Rene'88DT, Rene'104 and Direct Age 718. These datasets combined a large variety of stress ratios experimented under conditions of uniaxial loading, torsion, and proportional loading, as well as loading paths of non-proportional loads, which attest to the parameter versatility. The damage parameter is well adapted to predict the life of multi-axial fatigue in a system where elastic conditions predominate. For continuation to a low life system in which significant periodic plasticity may occur, this parameter may not be suitable.

## 6. Summery of previous research

After presenting all the studies and noticing the frequent multi-axial fatigue in industries, now it should be mentioned that combined loads caused to multi-axial fatigue phenomena should be studied for all complex loading conditions for different geometric specimens. Also, there are no exact details about the multi-axis fatigue machines and the working mechanism, especially in the non-proportional loading, which makes manufacturing similar devices a little complicated. Besides, most of the published papers in multi-axial fatigue confuse model a criterion? by using previous experimental test results to compare with new multi-axial fatigue models without updating the experimental test.

## 7. Conclusion

This paper provides a universal case review for the mechanism of multi-axial fatigue subjected to proportional and nonproportional loading. The majority of studies on total fatigue in life estimation are based on loading path and phase angle. The various multi-axial fatigue devices presented in the literature have emerged based on the approach taking on combination loads: tension-torsion and bending-torsion. Also, in this paper, the multi-axial fatigue models have been shown and classified into four models depending on different theories. Overly, predicting fatigue life accurately for the components under nonproportional complex loads will prevent unexpected failure under a real operation.

## 8. References

[1] E Zahavi, V Torbilo and S Press 1996 *Fatigue Design: Life Expectancy of Machine Parts* CRC press, 1996
[2] K J Miller and M W Brown 1984 *Multi-Axial Fatigue: A Brief Review*," in *Fracture 84* (Elsevier) pp 31–56
[3] D Socie and G Marquis 1999 *Multi-Axial Fatigue* (Warrendale Soc. Automot. Eng.) vol 502 p 1999
[4] D Socie 1993 *Critical Plane Approaches For Multi-Axial Fatigue Damage Assessment* (in Advances in multi-axial fatigue, ASTM International)
[5] R I Stephens, A Fatemi, R R Stephens and H O Fuchs 2000 *Metal Fatigue in Engineering* (John Wiley & Sons)
[6] A R Kallmeyer, A Krgo and P Kurath 2002 *Evaluation of Multi-Axial Fatigue Life Prediction Methodologies for Ti-6Al-4V* (J. Eng. Mater. Technol) vol 124 no 2 pp 229–237
[7] A Krgo 2000 *Evaluation of Multiaxial Fatigue Life Prediction Methodologies for Ti-6A1-4V Under High Cycle Fatigue Loading* (North Dakota State University)
[8] D L Morrow 1989 *Biaxial-Tension Fatigue of Inconel 718*
[9] N E Dowling 2007 *Engineering methods for deformation, fracture and fatigue, Mechanical Behaviour of Materials* (Prentice Hall, USA)
[10] F K M Guideline 2003 *Analytical Strength Assessment of Components in Mechanical Engineering* (Norma, Frankfurt/Main: Forschungskuratorium Maschinenbau (FKM)) vol 5
[11] M W Brown and K J Miller 1973 *A Theory For Fatigue Failure under Multi-Axial Stress-Strain*

*Conditions* (Proc. Inst. Mech. Eng.) vol 187 no 1 pp 745–755
[12] E Krempl 1974 *The Influence of State of Stress on Low-Cycle Fatigue of Structural Materials. A Literature Survey and Interpretive Report* (in The Influence of State of Stress on Low-Cycle Fatigue of Structural Materials: A Literature Survey and Interpretive Report, ASTM International)
[13] S-B Lee 1985 *A Criterion For Fully Reversed Out-of-Phase Torsion And Bending* (in Multi-axial fatigue, ASTM International)
[14] Y S Garud 1981 *Multi-Axial Fatigue: A Survey of The State of The Art* (J. Test. Eval.) vol 9 no 3 pp 165–178
[15] S-B Lee 1990 *Development of A Deflection Controlled Multi-Axial Fatigue Testing Machine* (KSME J.) vol 4 no 2 pp 103–108
[16] S D Downing and D R Galliart 1985 *A Fatigue Test System for A Notched Shaft in Combined Bending And Torsion* (in *Multiaxial Fatigue*, ASTM International)
[17] B I Stoychev and S H Stefanov 2010 *Rotating Bending with Constant Torsion and Rotated Bending with Constant or Variable Torsion* (in Proceedings of the 9th international conference multi-axial fatigue & fracture (ICMFF9) Parma, Italy) pp 349–356
[18] B Van Hooreweder, D Moens, R Boonen and P Sas 2012 *Design and Simulation of A Novel Multi-Axial Fatigue Test Rig* (Exp. Mech.) vol 52 no 5 pp 513–524
[19] J Papasidero, V Doquet and D Mohr 2014 *Determination of the Effect of Stress State on the Onset of Ductile Fracture Through Tension-Torsion Experiments* (Exp. Mech.) vol 54 no 2 pp 137–151
[20] Rahmatollah Ghajar MG 2010 *Analysis of Mechanical Structures Under Multiaxial Fatigue* (Toosi Univ. Technol) pp 86–88
[21] H Gerber 1874 *Bestimmung Der Zulässigen Spannungen in Eisen-Constructionen* (Wolf)
[22] J Goodman 1899 *Mechanics Applied to Engineering. 1899* (London: Longman, Green & Company)
[23] G Sines 1959 *Behavior of Metals Under Complex Static And Alternating Stresses* (Met. fatigue) vol 1 pp 145–169
[24] M Erickson, A Kallmeyer, E Goodin, E Torkelson and P Kurath 2006 *An Evaluation of Multiaxial Fatigue Data from Ti-6Al-4V using a Critical Plane Methodology*
[25] Y S Garud 1981 *A New Approach to the Evaluation of Fatigue Under Multi-Axial Loadings* (J. Eng. Mater. Technol.)
[26] W N Findley 1959 *A Theory for the Effect of Mean Stress on Fatigue of Metals Under Combined Torsion and Axial Load or Bending* (J. Eng. Ind.) vol 81 no 4 pp 301–305
[27] J Papasidero, V Doquet and D Mohr 2015 *Ductile Fracture of Aluminum 2024-T351 under Proportional and Non-Proportional Multi-Axial Loading: Bao–Wierzbicki Results Revisited* (Int. J. Solids Struct.) vol 69 pp 459–474
[28] F Berto, A Campagnolo and P Lazzarin 2015 *Fatigue Strength of Severely Notched Specimens Made of Ti–6Al–4V under Multi-Axial Loading* (Fatigue Fract. Eng. Mater. Struct.) vol 38 no 5 pp 503–517
[29] J-S Blazy *et al* 2004 *Deformation and Fracture of Aluminium Foams Under Proportional And Non Proportional Multi-Axial Loading: Statistical Analysis and Size Effect* (Int. J. Mech. Sci.) vol 46 no 2 pp 217–244
[30] Z-R Wu, X-T Hu and Y-D Song 2014 Multi-axial fatigue life prediction for titanium alloy TC4 under proportional and nonproportional loading," *Int. J. Fatigue*, vol 59, pp 170–175, 2014
[31] Y-Y Wang and W-X Yao 2006 *A Multi-Axial Fatigue Criterion for Various Metallic Materials Under Proportional And Nonproportional Loading* (Int. J. Fatigue vol 28 no 4 pp 401–408
[32] Y Xiong, Q Yu and Y Jiang 2012 *Multi-Axial Fatigue of Extruded AZ31B Magnesium Alloy* (Mater. Sci. Eng. A) vol 546 pp 119–128
[33] A Bernasconi, M Filippini, S Foletti and D Vaudo 2006 *Multi-Axial Fatigue of A Railway Wheel Steel under Non-Proportional Loading* (Int. J. Fatigue) vol 28 no 5–6 pp 663–672

[34] F Berto, S M J Razavi and M R Ayatollahi 2017 *Fatigue Behaviour of Notched Specimens Made of 40crmov13 9 Under Multi-Axial Loading* (Procedia Struct. Integr.) vol 3 pp 85–92
[35] M Erickson, A R Kallmeyer, R H Van Stone and P Kurath 2008 *Development of A Multi-Axial Fatigue Damage Model For High Strength Alloys Using A Critical Plane Methodology* (J. Eng. Mater. Technol) vol 130 no 4