Equi-Biaxial Loading Effect on Austenitic Stainless Steel Fatigue Life

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ABSTRACT. *Fatigue lifetime assessment is essential in the design of structures. Under-estimated predictions may result in unnecessary in service inspections. Conversely, over-estimated predictions may have serious consequences on the integrity of structures.*
In some nuclear power plant components, the fatigue loading may be equi-biaxial because of thermal fatigue. So the potential impact of multiaxial loading on the fatigue life of components is a major concern. Meanwhile, few experimental data are available on austenitic stainless steels. It is essential to improve the fatigue assessment methodologies to take into account the potential equi-biaxial fatigue damage. Hence this requires obtaining experimental data on the considered material with a strain tensor in equi-biaxial tension.
Two calibration tests (with strain gauges and image correlation) were used to obtain the relationship between the imposed deflection and the radial strain on the FABIME2 specimen. A numerical study has confirmed this relationship.
Biaxial fatigue tests are carried out on two austenitic stainless steels for different values of the maximum deflection, and with a load ratio equal to -1.
The interpretation of the experimental results requires the use of an appropriate definition of strain equivalent. In nuclear industry, two kinds of definition are used: von Mises and TRESCA strain equivalent.
These results have permitted to estimate the impact of the equibiaxiality on the fatigue life of components.

INTRODUCTION AND AIM

The problem of multiaxial fatigue is a major concern and has been extensively studied in the literature. More or less innovative experimental means have been developed. However, some references which deal with the multiaxial aspect in steels show,

blatantly, the aggravating effect on multiaxiality and in particular of biaxiality on the fatigue curves. The service lives are significantly reduced [1-6].
Unfortunately, there is no experimental data available concerning fatigue strength for the austenitic stainless steels subjected to multiaxial loadings, which are used for power plants components. In order to obtain fatigue strength data under multiaxial loading, biaxial test means were developed at LISN. The particularity of this equipment is to consider only isothermal equibiaxial mechanical loadings, which are both in phase and proportional.
It will be possible to conclude from the tests conducted on the specimen “FABIME2” whether the austenitic stainless steel material is sensitive or not to the biaxial state loading in the high cycle fatigue regime.
On the other hand, tests undertaken by Poncelet et al. [6] on 304L austenitic stainless steel cruciform specimens have concluded that equibiaxial stress state is not detrimental compared with uniaxial fatigue. Another conclusion made by these authors is the penalizing effect of the mean stress.

THE EXPERIMENTAL DEVICE

The objective of this new experimental fatigue test is to dissociate the effect of the mean stress and equibiaxial state loading. Indeed, we try to obtain a negative load ratio in order to get the same results as the uniaxial data and eliminate the residual strain.
In this study, equibiaxial state loading generated from fatigue will be considered. It will be used to optimize the geometry of a disk specimen refined in its center. It is used as a circumferentially embedded diaphragm with an applied pressure on both sides in order to obtain an equivalent strain in each loading direction in the plane (Figure 1).

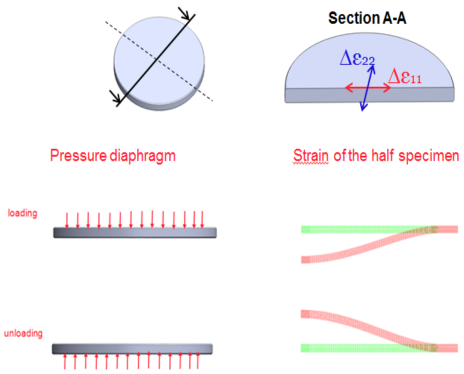


Figure 1. Principle of the new experimental fatigue test.

The experimental device called “FABIME 2” is divided into four parts [7]:

- Fatigue cell (Figure 2) which contains the spherical bending specimen
- Pressure generating system until 100 bars
- Electrical enclosure

- Homemade software developed under LABVIEW that provides control and acquisition data during the tests

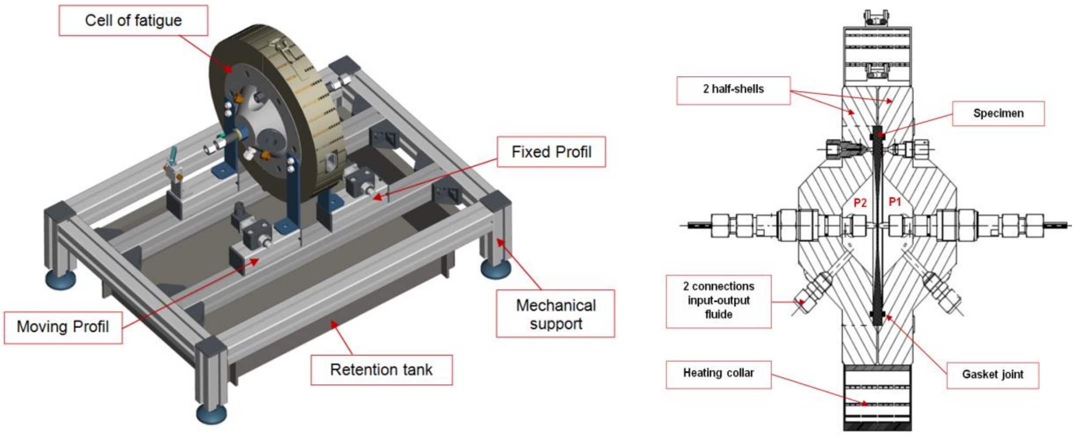


Figure 2. View of the spherical bending device and Technical view of the fatigue cell.

Two half-shells allow the positioning of the spherical bending specimen. Seal and embedment are realized by bolting these two parts. Maximum experimental conditions are 100 bars for the pressure and 90°C for the temperature. An alternative differential pressure between the two sides of the spherical specimen is applied during the fatigue test.
To ensure well-defined experimental conditions, various measuring means are located symmetrically at the two half-shells

- Pressure sensor with a measuring range between 0 to 100 bars
- Type K thermocouple to measure the temperature of the fluid inside the fatigue cell
- Displacement sensor (LVDT) to measure the deflection at the center of the spherical bending specimen. This sensor has a 5mm range. Realizations of surface observations after the fatigue test show that the contact between LVDT and specimen is negligible (no fretting). No crack initiation is also observed directly under the LVDT.
- Two visualization windows on each half-shell, oriented at 45° with a diameter of 20 mm. The constitutive material is borosilicate glass with a permissible operating pressure of 100 bars.

The fatigue cell is built under European Security directives (Machines 2006/42/CE, Pression 97/23/CE).

THE EXPERIMENTAL PROTOCOL

The experimental protocol is the following:

- Implementation of the spherical bending specimen, with a slight overpressure to ensure a first purge,
- Several blocks of 50 cycles with an increasing displacement loading. The aim of these steps is to ensure proper implementation of the components under the effect of pressure, and to ensure the best purge is possible.
- Beginning of the fatigue test at the chosen deflection with “slow” cycles every 500 cycles allowing taking photographs through the windows.

The objectives of these particular cycles is to taking into account the good value of the residual strain at no pressure due to the elasto-plastic behavior of the specimen. The “center” of the elasto-plastic loop behavior of the specimen can be estimate and the range of deflection is adjusting within this information.

The spherical bending fatigue test is stopped when cracks have propagated outside the central zone.

Calibration

Tests with the new experimental fatigue device are conducted with imposed displacement or deflection. In order to properly connect the strain level in the central area with the measured deflection, we need to define an experimental curve which represents the measured deflection versus the corresponding strains in this zone.

A calibration phase is necessary to obtained the appropriate curve [$\Delta\varepsilon_r$; Δdeflection] directly from experimental results, and with these methods, the obtained curve is taking into account the real mechanical behavior of the specimen.

Two experimental calibration methods have been carried out in the LISN laboratory with the FABIME2 device. Specimens used are in stainless austenitic steel type 316L [8].

Calibration with strain gauges

The first calibration test was performed with a specimen instrumented with 9 strain gauges:

- Delta rosette composed by 3 radial strain gauges located at the center of the specimen and inside a 5mm circle.
- 3 radial strain gauges between 20 mm to 300 mm of the center of the specimen
- 3 tangential strain gauges between 20 mm to 300 mm of the center of the specimen

Calibration with stereo correlation

The second calibration test is based on the technique of stereoscopy image correlation. In collaboration with “Videométric Technology” company and CEA laboratory “EMSI”, a speckle pattern was realized in the central area of the “FABIME2” specimen.

The specimen is placed in the fatigue cell using the same additional component as used in the first calibration method (strain gauges). Indeed, this additional part permits that the speckle pattern is completely visible for the picture acquisition. Reference picture with no pressure and picture for different levels of pressure were acquired. The pressure is thus applied unilaterally. The post processing of the experimental data obtained in the calibration test gave results with an error of 0.01 % in strain and a displacement measurement error equal to 0.2 μm.

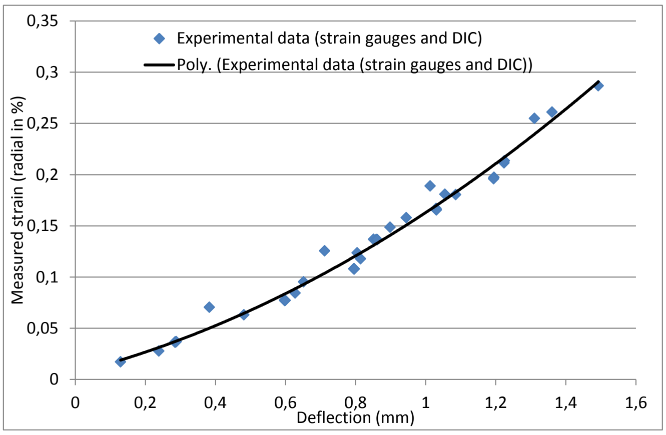
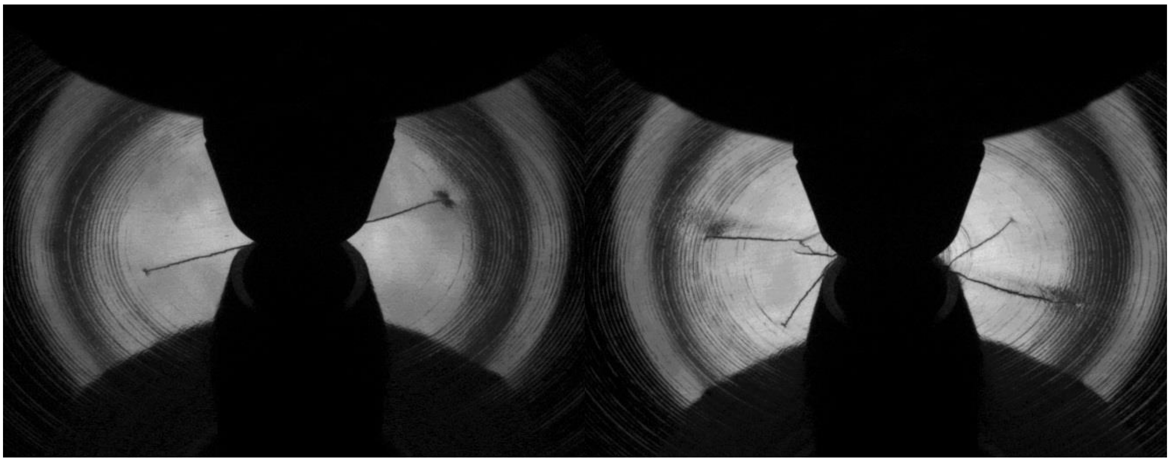


Figure 3. Deflection-strain calibration curve obtained on the fatigue device "FABIME2".

On the figure 3, experimental data obtained with the two calibration methods show the evolution of the radial train versus the deflection. Thus, we can conclude that the two experimental methods are in good agreement.

The crack initiation detection method

During the equibiaxial fatigue tests, two methods are used to determine the number of cycles corresponding crack initiation. The first one consists in following the change in the specimen compliance. The second corresponds to a visual detection through visualization windows on each half-shell.



a) propagation of crack at 16500 cycles b) propagation of crack at 22000 cycles

Figure 4. Image from the camera 2 (side 2) (a) and fomr the camera 1 (side 1) (b).

Some examples of images obtained from the camera on both sides are given below in figure 4. Four phases can be distinguished. The typical size of the detectable crack is about 5 mm in surface.

- No crack initiation
- First detection of crack initiation after 11500 cycles on side 2
- First detection of crack initiation after 16500 cycles on side 1, while crack is propagating on the other side (Fig. 4-a)
- Crack propagation on both sides during the fatigue test until the stop of the test (22000cycles) (Fig. 4-b).

It must be noted that on side 2, one single crack is propagating. On side 2, this same crack also exists, but other cracks also propagated in directions mainly perpendicular.

The Experimental results

Biaxial fatigue tests are carried out on two austenitic stainless steels: “316L THY”, and “304L CLI”. The first material has been provided by Thyssen Krupp Materials France as a 15mm thickness rolled sheet. The second material supplied by EDF is characterized by a thickness of 30 mm rolled sheet.

The first fatigue test campaign is performed on austenitic stainless steel type 316L. Five levels of deflection are studied: 1.6 / 1.4 / 1.2 / 1.1 and 0.9 mm.

In the frame of CEA-EDF-AREVA working group, a second fatigue test campaign is performed on austenitic stainless steel 304-CLI provided by EDF. This material completely agrees with the RCC-MRx [9] and RCC-M [10] specification. Three levels of deflection are carried out 1.4 / 1.3 and 1.2 mm.

INTERPRETATION OF THE EXPERIMENTAL RESULTS

All tests performed in this study are carried out with imposed displacement (strain) with alternating load (without mean stress or strain), means with a stress ratio R=-1.

To compare the experimental data obtained from uniaxial and equibiaxial tests, it is necessary to define a total equivalent strain.

Two definitions of equivalent strain are proposed: the first is based on the definition of von Mises (used in the RCC-MRx) and the second on the definition of TRESCA (used in the RCC-M, RSE-M).

The proposal approach to determine the level of the equivalent strain for each FABIME2 test is as follows:

- Determination of the value of the radial strain corresponding to the imposed deflection from the strain-deflection calibration curve obtained in the previous part of this paper. With a similar mechanical behavior, the calibration curve can be used for the two materials (Figure 3).
- Determination of the von Mises or TRESCA equivalent strain from the relation between the radial strain and the equivalent strain (von Mises or TRESCA). This relation has been determined by elasto-plastic calculation of the fatigue test.

Theses elastic-plastic behavior computations are used to determine the "real" value of the Poisson's ratio by taking into account the elastic and plastic part.

This method has been applied to the equi-biaxial fatigue tests presented earlier. The corresponding fatigue life curves are compared to that under uniaxial loading in Figure 5. It appears that there is also no impact of equi-biaxial fatigue for the two types of materials, considering both von Mises and TRESCA equivalent strains.

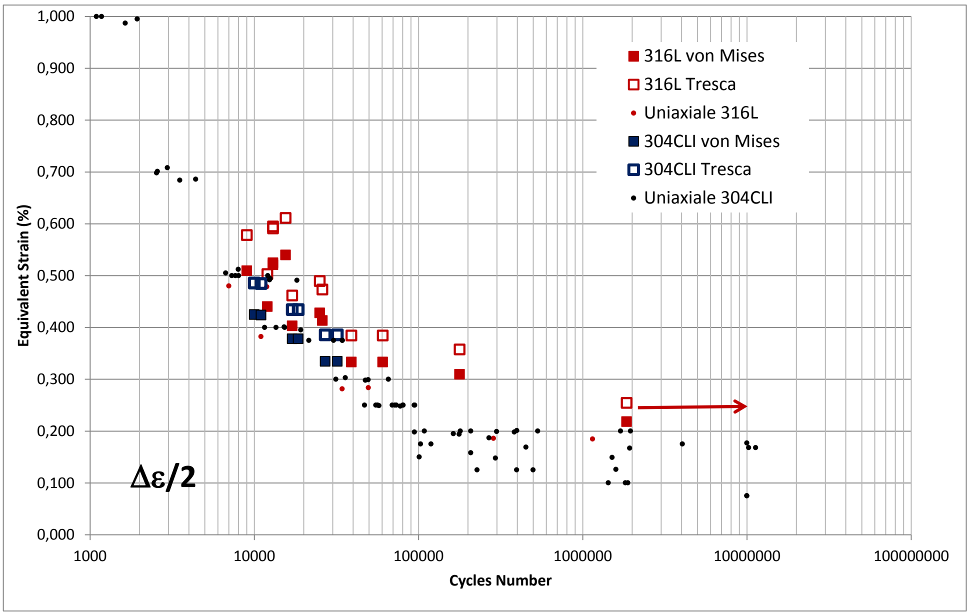


Figure 5. Austenitic stainless steel fatigue curve for 304L-CLI and 316L under uniaxial and equibiaxial loadings

CONCLUSIONS

This paper is focusing on the study of the impact on the equibiaxiality on the fatigue curves. A new experimental FABIME2 device has been developed at LISN. Two calibration tests (with strain gauges and image correlation) were used to obtain the relationship between the imposed deflection and the radial strain on the FABIME2 specimen.

Biaxial fatigue tests are carried out on two austenitic stainless steels: 316L THY and 304L CLI for different values of the maximum value of deflection, and with a load ratio equal to -1.

The interpretation of the experimental results requires the use of an appropriate definition of equivalent strain. In nuclear industry, two kinds of definition are used: von Mises and TRESCA equivalent strains.

The results obtained during the experimental campaigns carried out in the context of our study and for two austenitic stainless steels submitted to equibiaxial loadings show that crack initiation have a low impact on the fatigue life, which remains in the field covered by the design curve defined and used in the codification.

This FABIME2 device allowed the study of the impact of fatigue life on equibiaxial loadings and crack propagation in austenitic stainless steel. So, the device has the capability to study other different aggravating factors like surface roughness, mean stress or strain, residual stress, pre-hardening.

A new device based on FABIME2 is under development for the study of the impact of the environmental effect. This device will study the impact of the equibiaxial loadings with a primary water environment PWR (300°C with a permanent pressure of 140 bars).

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