CRACK INITIATION UNDER AN EQUIBIAXIAL FATIGUE, DEVELOPMENT OF A PARTICULAR EQUIBIAXIAL FATIGUE DEVICE.

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ABSTRACT

The estimated lifetime is essential in the design of structures. An under-estimated lifetime may result in additional costs due to significant additional controls and replacement parts. Conversely, an over-estimated lifetime may have serious consequences on the integrity of structures. Particularly in the context of thermal fatigue, experiences with different geometries, thermal loads as well as various environments (air, water and sodium), conventional methods of analysis and fatigue criteria are insufficient to correctly estimate the thermal fatigue resistance [1]-[5]. All these methods and fatigue criteria have been developed from a purely uniaxial state of stress. A new definition of strain equivalent has been introduced to take into account the biaxiality of the stress; this allows the application of fatigue analysis without modifying the existing fatigue curves. Development and proposal of new multiaxial criteria or methodologies to take into account properly the thermal fatigue damage require to obtained experimental data on the considered material and with a stress tensor in equibiaxial tension. This is the goal of an original device designed at the CEA-LISN. This experimental device and its results are presented in this paper. From these experimental results, a numerical interpretation is developed and described. From this numerical interpretation, mechanical states (variation of strain) are determined and a comparison with the fatigue curve of the same material is performed. A proposal for a multiaxial criterion is detailed, based on the work undertaken by ZAMRIK. This criteria provides an overview of the possibilities of this multiaxial fatigue criterion. At the end, this work aims to introduce the Zamrik criterion into nuclear codes and standards.

INTRODUCTION

The definition and validation of a multiaxial criterion to study thermal fatigue first requires experimental data about the considered material (austenitic stainless steel type – 304 or 316). Due to few experimental data available [6]-[9] in the literature, a specific facility has been designed in our laboratory to answer the problem of purely mechanical equibiaxial fatigue. The experimental facility is based on the principle of the 4-point bending, but towards a applied central axis: called spherical bending. Displacement and deformation measurements were used. The shape of the specimen has been optimized to ensure a crack initiation in the center of it. Using this original facility, twelve spherical bending tests were performed with different load ratio.

The numerical interpretation of these spherical bending tests was carried out with a plasticity model with a non-linear kinematic hardening model. An analysis based on the von Mises criterion was proposed, it showed that it is not adapted to the multiaxial case. A proposed multiaxial criterion is described. The particularity of this criterion is its capability in using standard codified fatigue curves obtained on uniaxial specimens. An analysis based on this proposed criterion is undertaken and provides the capability of this criterion for multiaxial fatigue.

The tests also revealed a structure effect.

SPHERICAL BENDING FATIGUE TESTS

Description of the principles of the spherical bending device

Multiaxial tests described in [6]-[9] and the most demonstrative one [9] show the influence of multiaxial loading on fatigue life of steels. However, there are no sufficient experimental data on the fatigue life for austenitic stainless steels subjected to multiaxial loadings used for power plant components. To obtain experimental data on multiaxial fatigue, the development of a biaxial fatigue device was undertaken at the laboratory (LISN). The particularity of this new device is to be limited to equibiaxial mechanical load, both in phase and proportional.

To apply the loading based on 4-point bending principle, the load is transferred to an axis of rotation which creates the biaxial state. The upper and lower rolls are replaced by different diameters cores.

The profile of the spherical bending specimen was optimized in order to focus the strain in the central active area. The main dimensions are 25 mm for the central active area, the radius of the upper core (44 mm) and the radius of the lower core (144 mm). The thickness of the central active area is 5 mm and the thickness of the loading zone (area of application of the load) is 15 mm.

A thickness transition on the upper side between the central active area and loading zone is introduced. This enables the specimen to always be in tension condition during testing as the active area is under the neutral line of the bending specimen. The profile of the spherical bending specimen is presented in Fig. 1 as well as its impact on the evolution of strain along the axis of the specimen (Fig. 1).

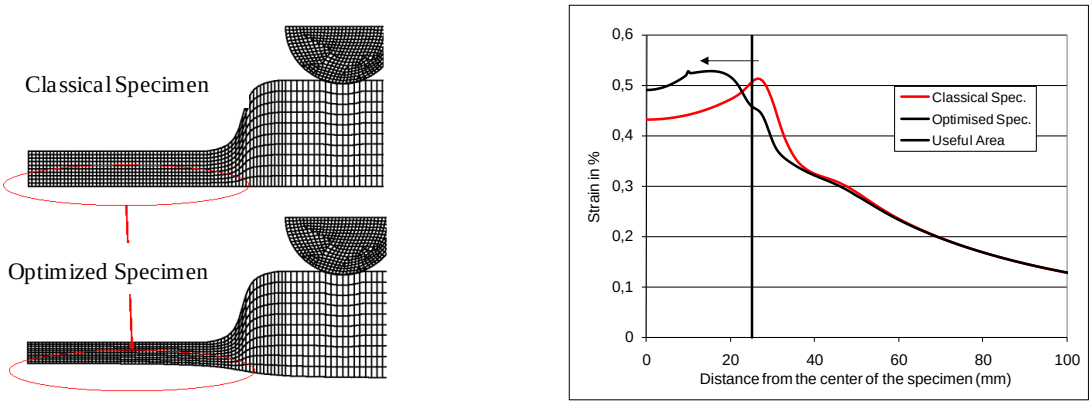

Fig. 1: Geometrical model of the spherical bending specimen and strain evolution induced by the modification of the profile of specimen

In addition to modifying the profile of the specimen, it was considered essential to implement different measurements to minimize the use of assumptions (material behavior) for the spherical bending test interpretation. One of them was to measure the deflection at the center of the specimen during testing. The advantage of using this type of measure is its independence with regard to the specimen geometries. The implementation of three strain gauges on the top of the active area and placed in star provides a measure of local strain in the radial direction. Experimental data are important to validate the material behavior and numerical assumption for the numerical interpretation of these tests.

Fatigue tests

A specific driving mode was implemented to carry out the fatigue tests on the spherical bending bench, combining a displacement loading and a strength unloading (cf. Fig. 2). Thus, the test conditions are:

- Displacement control during the loading phase (the relative amplitude is defined and compared to the last position at zero force (-1 kN), the amplitude value decrease from -1.25 to -2mm at a speed of 1mm/s)
- Strength control during the unloading phase (-1 kN to avoid separation of upper core with the specimen) at the speed of 50kN/s
- Number of cycled fixed (at the end of a defined number of cycles a liquid penetrant test is done to highlight a crack initiation)
- The cycle frequency is about 0.1 à 0.5 Hz.

During the experimental spherical bending campaign, two types of tests were conducted. The first type corresponds to an unloading return to zero force (-1kN), and the second to an unloading return to non-zero force (-25kN or -40kN) to increase the average stress. The load ratio is thus very different.

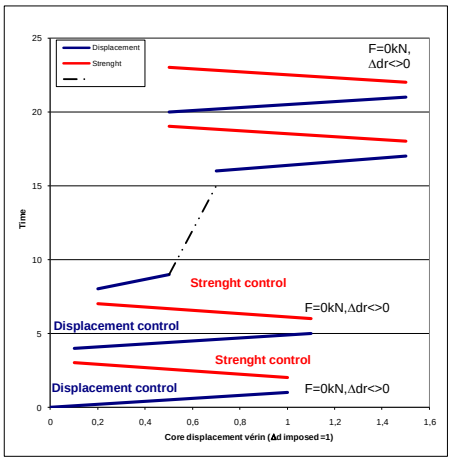

Fig. 2 : Description of the spherical bending combining control

Fatigue tests with a return to zero force (-1kN)

This experimental spherical bending campaign, composed of seven tests was conducted with a return to zero force. For each test, we find in figure 3 and 4 an illustration of some results of liquid penetrant test performed after full crack propagation.

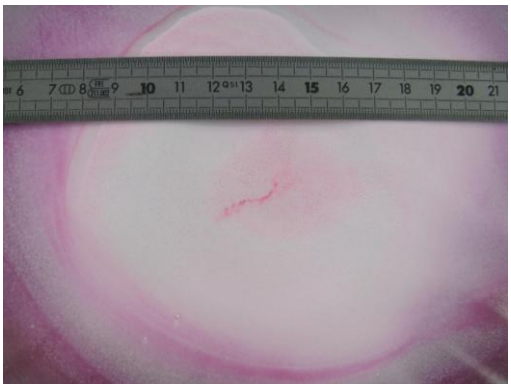

Fig. 3 : Liquid penetrant test result to the specimen number 4

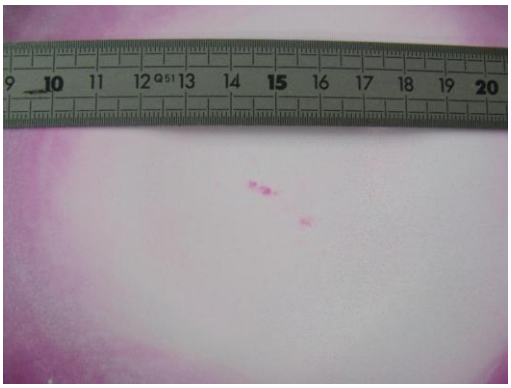

Fig. 4 : Liquid penetrant test result to the specimen number 5

The crack initiation occurred in the center of the active area of the specimen for all fatigue tests, which validates the optimization of the proposed profile.

Fatigue tests with a return to non-zero force (-25kN or -40kN)

An experimental second spherical bending campaign was conducted and it was intended to identify whether the effect of a higher load ratio existed. These fatigue tests were carried out with an greater average stress than the previous campaign. The return to zero force (-1kN) is replaced by a return to a given different force (-25kn and -40kN).

The experimental data obtained during a test (F_{return} = -25kN) are presented below. The mechanical behavior during bending tests with and without a return to zero force is similar. There is a rapid increase in the maximum strength followed by stabilization to the first hundred cycles. These evolutions and stabilizations are represented on the following figures.

The evolution of the deflection is slower to stabilize and it usually changes very slightly. On the following figure, we see a lower stabilization than that of the strength, but it is relatively fast (about 1000 cycles). Then, the deflection increases slowly until the crack initiation.

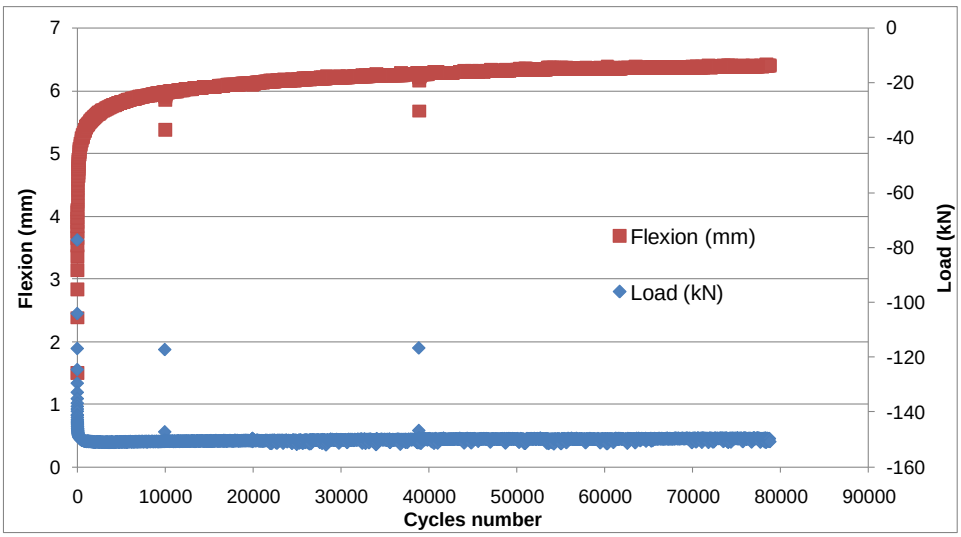

Fig. 5 : Evolution of the deflection and the strength during a test.

Table 1 : Experimental data obtained during multiaxial fatigue test with the spherical bending device.

Test number	Imposed displacement (mm)	Measurement deflection (mm)	Number of cycles to initiate	Freturn (kN)	Total strain variation (%)	Von Mises equivalent strain variation 5%)	Residual deflection (mm)
2	2		15000-19300		0,355	0,438425	
3	1,5		723000-92300		0,228	0,28158	
4	1,5	1,63	125000-135000		0,208	0,25688	0,6
5	2	2,5	35000-40000		0,323	0,398905	1,04
6	1,75	2,125	81000-90000		0,273	0,337155	0,95
7	1,25	1,4	240000-300000		0,178	0,21983	0,54
8	1,75	2,05	130000-140000		0,268	0,33098	0,9
9	1,75	2,25	60000-61000		0,296	0,36556	0,76
10	1,5	1,99	85000-90000	-25	0,262	0,32357	4,92
11	1,25	1,62	202000-206000	-40	0,213	0,263055	3,34
12	1,25	1,609	195000-215000	-40	0,212	0,26182	2,92

During the spherical bending campaign tests, twelve specimen tests were performed. The strain variations are directly obtained from experimental measurements, no numerical interpretation is made for the moment. All points are below the material fatigue curve corresponding to that obtained on laboratory specimens [2]. The numbers of cycles to initiate cracks are even close to the design fatigue curve from the RCC-MR [10]

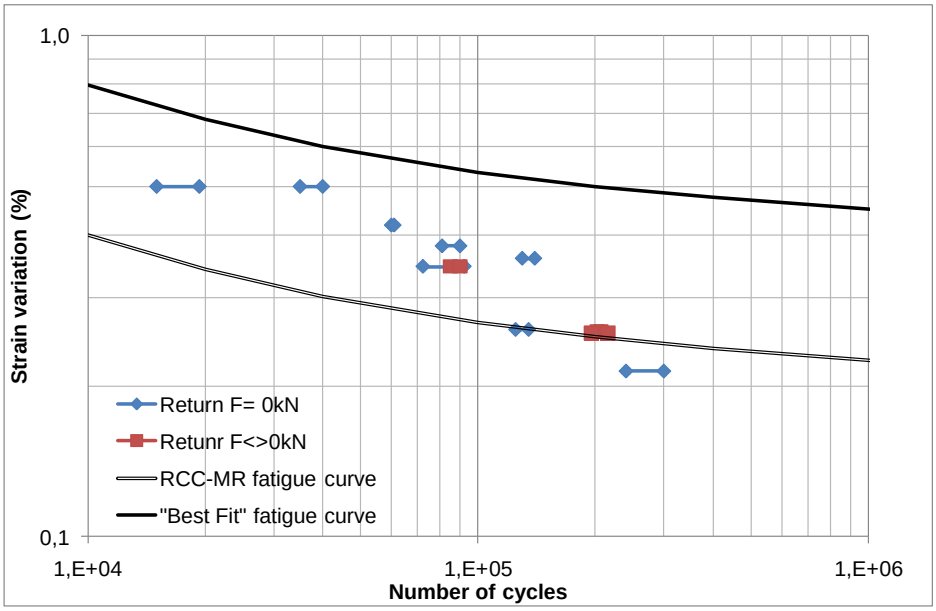

Fig. 6 : Fatigue experimental data obtained with spherical bending device

SPHERICAL BENDING TEST INTERPRETATION, ESTIMATION OF THE EQUIBIAXIAL FATIGUE LIFE, PROPOSED AN EQUIBIAXIAL CRITERION

Numerical model used of the numerical interpretation

The implemented geometrical model consists of 2nd degree elements, with the axisymmetric assumption. Numerical interpretations of the spherical bending test are carried out considering two types of material behavior:

- a linear elastic material law
- a plasticity law with a kinematic and non-linear hardening

Interpretations based on the plasticity material model can reproduce more accurately the observed non-linear behavior during the test. This model involves isotropic and non-linear kinematic hardening. It is implemented in the computation code Cast3M, as we used it.

The non-plasticity criterion is expressed by:

$$f(\sigma, X, R) = \sigma_2(\sigma - X) - R(p) \leq 0$$

The isotropic hardening variable R get the following form, according to the cumulative plastic strain p:

$$dR = b(R_m - R)dp$$

Where R_m is the asymptotic value when the cumulative plastic strain tends to large enough values. We also define in the model the initial value of the isotropic hardening R_0. The b parameter is a constant material which has to be identified.

The non-linear kinematic hardening X is defined by:

$$dX = C\left(\frac{2}{3}Ad\varepsilon_p - Xdp\right)$$

The model parameters were identified from uniaxial testing, the comparison with experimental data is shown on Fig. 7.

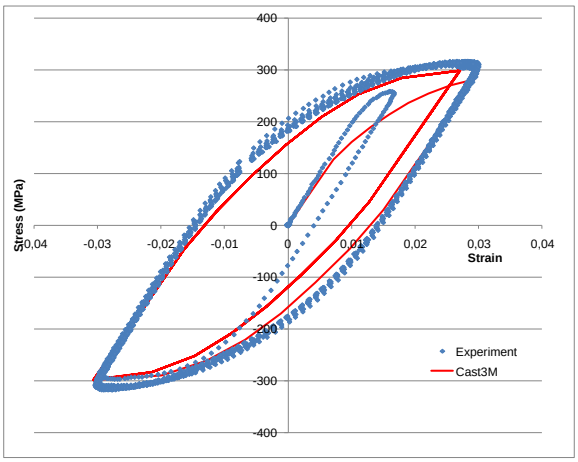

Fig. 7 : Identification of the parameter of the material behavior model

Estimation of the fatigue life (Zamrik multiaxial criterion) [11]

It is a multiaxial criterion based on strain. The proposed criterion by ZAMRIK is based on reflections carried out by Manson and Halford who have proposed a criterion for estimating the fatigue life under multiaxial loads. The equivalent strain is partitioned in an elastic part and a plastic part. The elastic part is unchanged, whereas the plastic part is modified by introducing a coefficient MF depending on the triaxiality factors so that:

$$\Delta\varepsilon_{eq}^{t} = \Delta\varepsilon_{eq}^{e} + MF\Delta\varepsilon_{eq}^{p}$$

$$MF = TF \text{ pour } TF \geq 1$$

$$MF = \frac{1}{2 - TF} \text{ pour } TF < 1$$

The triaxiality factor TF represents the ratio between the first stress tensor invariant and the von Mises equivalent stress ($TF = 3\sigma_H/\sigma_{eq}^{VM}$).

The effect of an equibiaxial loading is highlighted, a perfect equibiaxial loading clearly increases the damage by amplifying the equivalent strain, since MF=2. Conversely, a perfect torsion loading, clearly decreases the damage by reducing the equivalent strain MF=1/2. A perfect uniaxial tension gives MF=1.

From the same form, ZAMRIK proposed a multiaxial criterion as follows

$$\Delta^{*}\varepsilon_{eq}^{t} = A.\Delta\varepsilon_{eq}^{e} + B.\Delta\varepsilon_{eq}^{p}$$

In the general case, equivalent total strain is given by

$$\Delta^{*}\varepsilon_{eq}^{t} = \left(Z^{TF-1}\right)\Delta\varepsilon_{eq}^{e} + \left(\Lambda^{1-TF}\right)\Delta\varepsilon_{eq}^{p}$$

For 316L austenitic stainless steel tested at 621°C, ZAMRIK criterion values are Z = 1.42 et Λ= 1.8.

The triaxility rate of a structure subjected to equibiaxial loadings is strictly greater than 1 and equal to 2. Using the Zamrik criterion gives a lower fatigue life, which indicates the same trends as experimental observations.

Application of the fatigue criteria

The numerical interpretation by implementing an elastoplastic behavior model allows to obtain the elastic and plastic part of the strain during a loading sequence (variation of displacement) after ten cycles. The obtained strains are summarized in the following table.

Note that the values of equivalent elastoplastic strain obtained with the method of the K_v plasticity correction [10] are substantially identical to those obtained with the elastoplastic behavior model.

From these data, we can represent the points of fatigue life with the von Mises criterion. The curves are a reminder of the one presented in the experimental section (see Fig. 6).

The proposed Zamrik multiaxial criterion requires to determine the partition of elastic and plastic part of the strain. This was obtained using the numerical interpretations

From these data, we can represent the points of fatigue life with the proposed multiaxial criterion for thr tests conducted during the campaign (see Fig. 8).

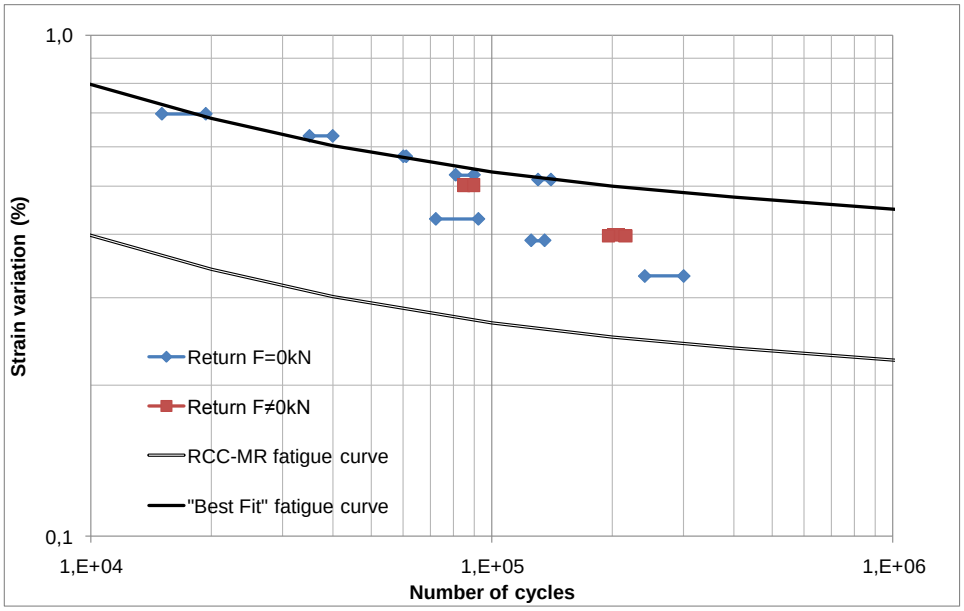

Fig. 8 : Fatigue curves obtained with an elasto-plastic interpretation and the use of the ZAMRIK criterion

Using the ZAMRIK multiaxial criterion enables to take into account the multiaxiality and to compare the fatigue points obtained on laboratory specimens with uniaxial fatigue point and fatigue point obtained with spherical bending specimens. The parameters identified by ZAMRIK seem to be sufficient in the context of the first approach and until we have more experimental data, to be applied to spherical bending test.

GENERAL CONCLUSIONS

The spherical bending fatigue tests were interpreted with two multiaxial criteria; the first is the commonly used von Mises criterion and the second corresponds to a criterion originally proposed by ZAMRIK to take into account the multiaxiality.

Using the von Mises criterion to evaluate the fatigue life of spherical bending specimen overestimates the number of cycles to crack initiation. The differences in the level of strain variation are determined and compiled in the following table.

Number of cycles	Strain variation for the spherical bending tests (%)	Strain variation for the uniaxial tests (%)	Difference (Exp/Prev)
125000-135000	0.258	0.49	183 %
35000-45000	0.42	0.52	124 %
81000-90000	0.356	0.50	140 %
240000-300000	0.208	0.46	223 %

Tab. 2 : Comparison between the uniaxial and multiaxial strain with the von Mises criterion

From the work initiated by ZAMRIK to define a criterion to take into account the multiaxiality, a criterion is proposed and written as follows:

$$\Delta^{*}\varepsilon_{eq}^{t} = \left(Z^{TF-1}\right)\Delta\varepsilon_{eq}^{e} + \left(\Lambda^{1-TF}\right)\Delta\varepsilon_{eq}^{p}$$

The experimental campaign results were interpreted with this proposed criterion and multiaxial fatigue points obtained are shown in the previous figure (see Fig. 8).

The lifetimes estimated with this criterion are comparable to those obtained with the “best fit” material fatigue curve. With this criterion, it is possible to compare two kinds of tests, uniaxial and multiaxial.

The experimental campaign was interpreted by the implementation of a new numerical model. These simulations used an elasto-plastic behavior model which was identified from uniaxial test performed on the same material. The numerical interpretation provides some answers on two points:

- Determination of the partition of strain between the elastic and plastic part, application of a proposed criterion,
- Estimation of the observed experimental residual strain

The test also revealed a structure effect. The tests are performed with a positive load ratio, and non-symmetrical loading cycles generate a residual strain. The evolution of this residual strain is similar for all types of tests. For spherical bending tests, there is indeed a structure effect (a part of the specimen remains elastic and prevents the increase of strain) that does not exist for uniaxial tests.

Thus, to clarify the impact of this residual strain with regard to the multiaxiality, the achievement of 4 points bending tests would provide important elements of understanding. Another solution would be to annihilate the residual strain by testing specimens with a negative load ratio. A further work would be to make alternating spherical bending test.

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