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# ANALYSES OF STRAIN LOCALISATION IN HDPE BUTTERFLY SPECIMEN DURING BIAXIAL TESTS USING DIGITAL IMAGE CORRELATION

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**Abstract.** This work presents a study of high density polyethylene (hdpe) strain under biaxial loading. An Arcan apparatus is achieved in order to load a newly-designed flat specimen called "butterfly specimen" to various combinations of tensile and shear loading. These specimens have a central region with a minimal thickness (1mm); witch constitutes a small area where the strain and the stress should be uniform before necking. All tests are conducted on an Instrone tensile machine at constant speed of the upper cross-head (v = 0,5 mm/min) at the ambient temperature. Displacement fields are measured in the central area of the specimens, during the tests, by coupling digital image correlation (DIC) with imaging using high-speed CCD cameras placed in front of the specimen. The experimental results show a strain localisation in the specimen gauge section.

## 1 INTRODUCTION

The diversity of polyethylene applications, particularly of the high density polyethylene (HDPE), made of him a material which receives a double attention over the years. Indeed, it is considered as a material model for the scientifics for the study of the semicrystalline polymers. The mechanical answer of the hdpe in uniaxial loading was the subject of several studies [1-7]. However, in main applications the material is submitted to multiaxial stress stat, what makes important the investigation of its behavior in these conditions. Few works have been achieved on polymeric materials behavior under multiaxial loading [8,9]. Recently, works on the epoxy, the polyethylene and the polypropylene in biaxial loading were based on tensile (or compression) tests combined to an internal pressure on hollow tubes [10-13] and on pvc and hdpe in biaxial tension [14]. The authors studied the yielding and fracture of these materials and strain rate and temperature effects on their behavior. In biaxial loading, the choice of the specimen shape and the test method used is imperative. The use of new particular shape specimens (butterfly specimens) developed initially by Bao and al [15,16] permit to develop a plane stress states in the central gauge section of these specimens when they are submitted to biaxial loading. It's an interesting advantage for the investigation of the strains field measurement in specimens during biaxial tests. Therefore, the purpose of the present work is to investigate the strain field localisation in the central section of this category of specimen for hdpe material under biaxial loading. In order to subject the butterfly-shaped hdpe specimens to combinations of shear and tension, a specific Arcan apparatus is used [17]. By suitably changing of the specimen orientation with respect to the loading direction (vertical displacement of upper cross-head of the tensile machine), different stress states would develop in the specimen gage section: from pure tension, combined tension and shear, to pure shear. The investigation of strain fields was performed by using digital image correlation (DIC). With this method it has been possible to observe the local mechanical behaviour of many materials like metals, ceramics and polymers [18–20] and it can achieve good reliability and accuracy for the strain mapping of the planar deformation of flat object.

The present paper is organized as follows. In Section 2, we present the specimen geometry and the mechanical testing protocol with the application of the DIC technique to evaluate the strain fields. The experimental results are presented and discussed in Section 3 and the conclusion is given in the section 4.

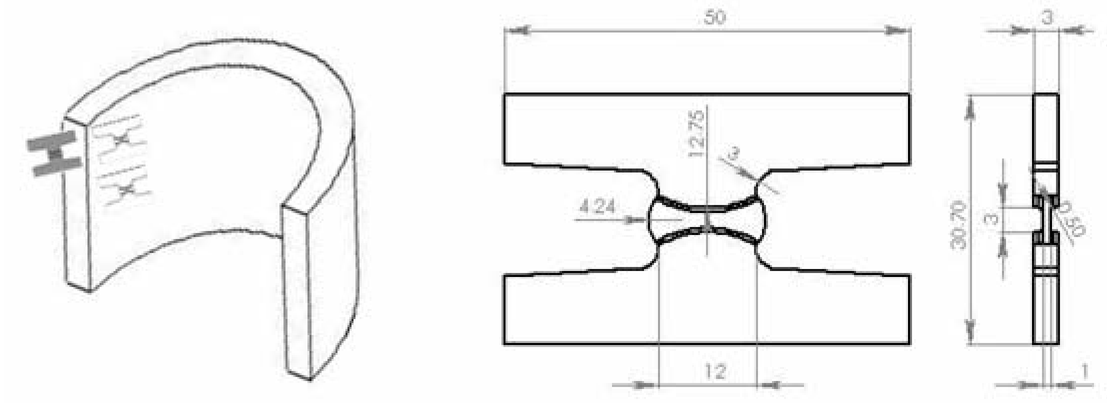
## 2 EXPERIMENTAL METHOD

### 2.1 Specimen preparation

The material investigated in this study is a high density polyethylene (hdpe). Its main characteristics are given in Table 1. The specimens used were machined from the same tube exhibiting an outer and inner diameter of 250 mm and 214mm respectively. These specimens were cut off in the extrusion direction (fig.1.a). They have complex, double curvature geometry in the gauge section. To hold the specimen securely, two long shoulders are designed to provide sufficient gripping (fig.1.b). The central region with a minimal thickness (1mm), much smaller than the thickness of the shoulder region (3mm), constitutes a small area where the strain and the stress should be uniform before striction.. This new type of specimens called butterfly specimen was first developed by Bao and al [15,16] and was successfully used to calibrate the fracture properties of A710 steel in biaxial loading. In the recent literature, similar specimens are used by Mohr and Henn to calibrate a crack formation criteria for metals [21, 22]. As well, it has also been applied to other materials as the alloys of aluminium [23, 24] and the PP/EPR/TALC blend [25].

**Table1:** Physical properties of studied HDPE

| | |
|---|---|
| Volumic Mass | 930 $Kg/m^3$ |
| Middle Mean molar mass $M_w$ | 310 000(g/ mole) |
| cristallinity rate $X_c$ | 66% |
| Melt temperature $T_f$ | 128,8°C |
| Indices of fluidity | 0,2-1 ;4 g/10(min) |




**(a)** **(b)**

**Figure.1. (a)** Extraction of specimens from the PE-pipe.
**(b)** Shape and dimensions of the butterfly specimen

## 2.2 Biaxial tests

The Arcan apparatus has been proposed initially by Arcan and al. [26] in order to study the reinforced composites behaviour in biaxial loading. The method was also recently applied to investigate the yield behavior of aluminum foams by Doyoyo and Wierzbicki [27]. In this present work, the device that we conceived and achieved is composed of two semi-circular steel plates fixed to the tensile machine by intermediate grips. The displacement of the half superior disk is oriented vertically in the loading direction by guide rods. Any rotation or misalignments of specimens are prohibited during the tests. Figure 2 illustrates a butterfly specimen mounted in the device with the orientation angle α=60° to the vertical. By suitably changing the specimen orientation with respect to the loading direction (vertical displacement of upper cross-head of the tensile machine), different stress states would develop in the specimen gage section: pure tension, combined tension and shear; and pure shear. The vertical reaction forces of the specimens were measured by a load cell. All the tests are conducted on an INSTRÖN hydraulic tensile machine at constant speed of the upper cross-head (v =0,5 mm/mn) at the ambient temperature.

## 2.3 Digital images correlation technique

The digital image correlation method (DIC), developed since the 80s [28-30] is based on comparison of two images in random gray levels recorded before and after deformation. The first image is called "reference" and the second "deformed" [31]. Displacement vectors are determined by comparing the two pictures. The first picture is divided into small subwindows. The discrete matrix of the values of the pixel grey level in each subwindow forms a unique fingerprint identification within the image. Therefore, at every ‘point’, i.e., at every subwindow center, it is possible to determine the in-plane displacement vector (figure 3).

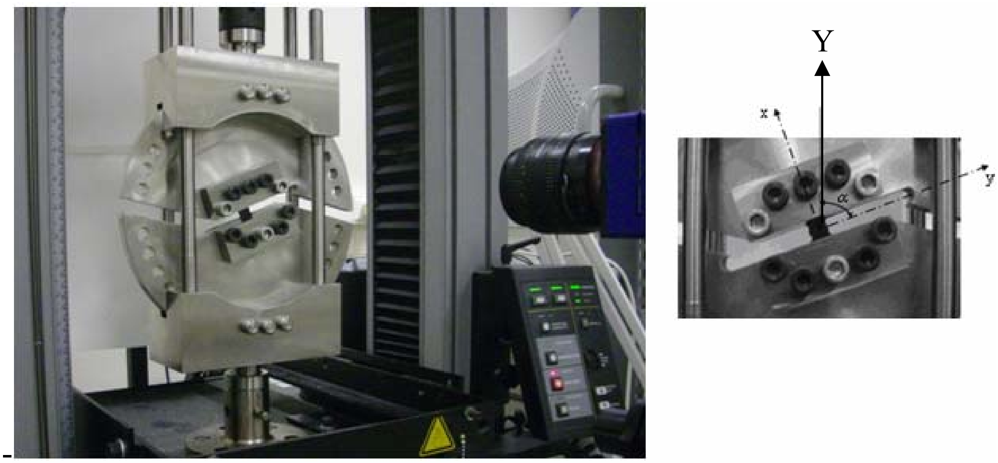



**Figure.2.** Arcan apparatus with a butterfly PE specimen

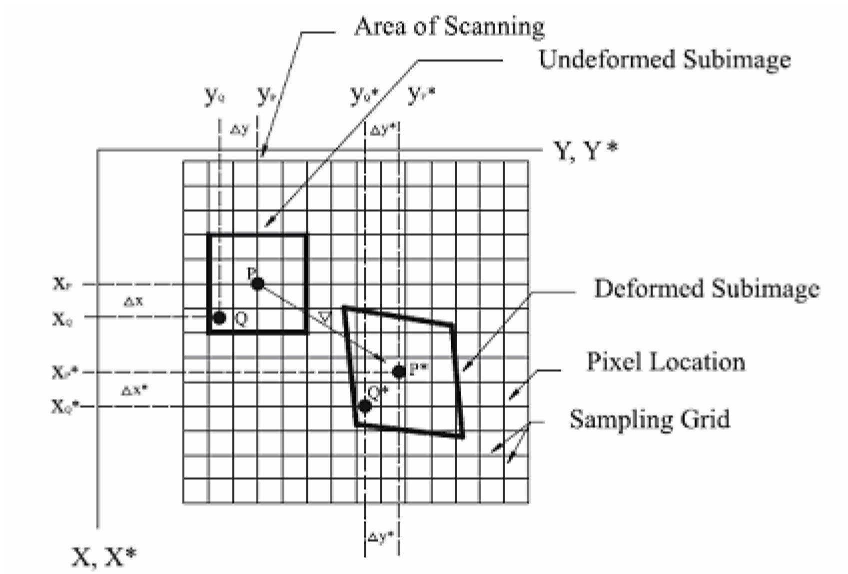



**Figure.3.** Schematic drawing of relative location of sub-images of the deformed and undeformed images on surface [32]

In this study, a random speckle pattern is obtained by spraying the butterfly specimen surface with white paint (Figure 4). The sample surface is illuminated with white light and images are taken by a CCD camera (1376x1040 pixels) mounted on an adjustable support. The distance between the specimen and the camera is adjusted so that the study area is focused in the camera along the test (figure 2). These images are stored throughout the test in a PC by Davis© software. It scans and sets the speckle after treatment for each recorded image mapping planar points. In the images, the user selects the area of study called "mask" which contains a set of points (pixel cells) where he wishes to measure. Thus, when the correlation between two images, each "point" will provide the value of the displacement vector. By derivation of the displacement field, we obtain the deformation field of the study area.

In our case, the mask is a rectangle ($13x3mm^2$) delimiting the central region of the specimen butterfly (figure 4). Each "point" measurement is a small area of the image $36x36pixels^2$ containing a sufficient number of random patterns to be unique within the scope of the image. Displacement fields are determined by correlation in absolute mode: images acquired successively during the test are compared to the original image (no distorted). The operation is repeated for all the images recorded during the test. The displacement field of the set of points of the mask is obtained, which allows, by deriving, for the strain field around the mask concerned.

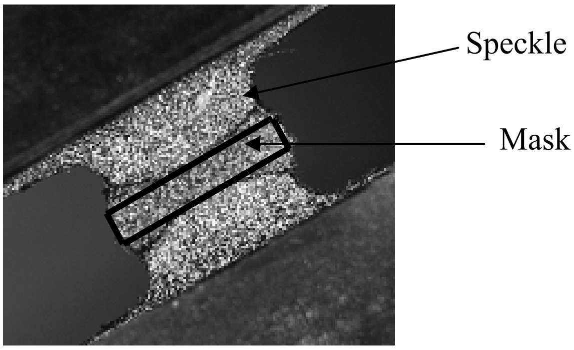



**Figure.4.** Random speckle pattern on butterfly PE specimen

## 3 RESULTS AND DISCUSSION

Positive vertical displacements were applied on the butterfly specimens at different loading angles. In this study we consider three tests: pure tensile (α = 90°), combined tensile and shear (α = 45°); and pure shear (α = 0°). The figures 5, 6 and 7 shows the Load–displacement curves and the corresponding strain-displacement curves obtained from DIC calculation in linear elastic response for the loading angle α = 90°, α = 45° and α = 0° respectively.

In the load displacement curves, we observe an initial linear elastic response followed by a nonlinear response which becomes increasingly nonlinear with increasing displacement up to reach almost a zero slope. The only divergence from this trend is seen for the loading angle of 90° which exhibit a significant load softening after the rollover to yield prior to load stabilization. The peak load denotes the onset of necking at the central section and this is due to the uniaxial tensile stress state which prevails at this loading angle.

The strain-displacement curves obtained from DIC calculation show the evolution of the in-plane deformation gradients: Eyy, Exx and Exy according to the vertical displacement in the middle of the butterfly specimen.

The strain map obtained by means of DIC measurements at the yield point shows that the strain fields are localised in the central section of the butterfly specimens for the three loading angle considered (α = 90°, α = 45° and α = 0°) (Figure. 8) and one can clearly observe that for α = 45° particularly, all the strain gradient components are localised in this area.

The observations on the global response are confirmed by this DIC strain results. Especially, the transition from a planar tension-dominated state for α = 90° to a shear-dominated state for α = 0° is well transcribed by these local data. In fact, the values of Eyy and Exy are considerably higher than the other components values for α= 90° and α= 0 respectively..

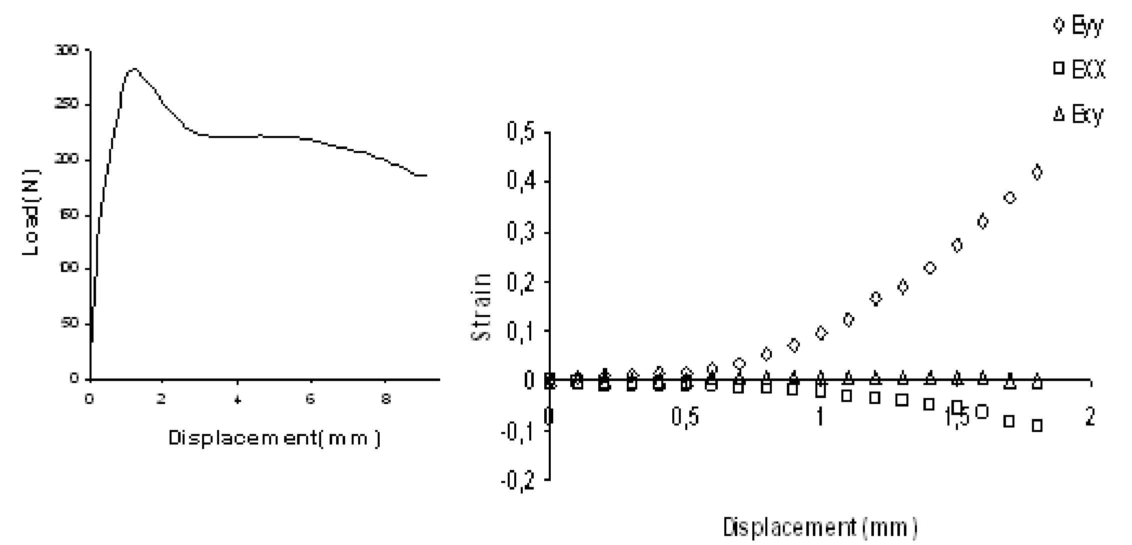



**Figure.5.** Load-displacement response of the butterfly-shaped specimen and strain-displacement curves obtained from DIC calculation for $\alpha = 90°$

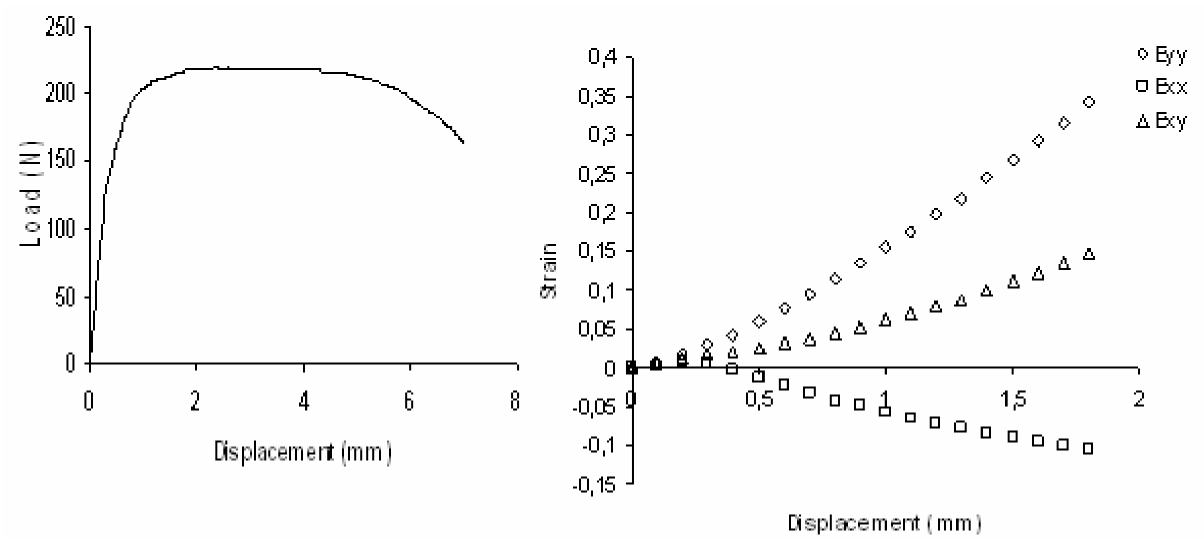



**Figure.6.** Load-displacement response of the butterfly-shaped specimen and strain-displacement obtained from DIC calculation for α = 45°

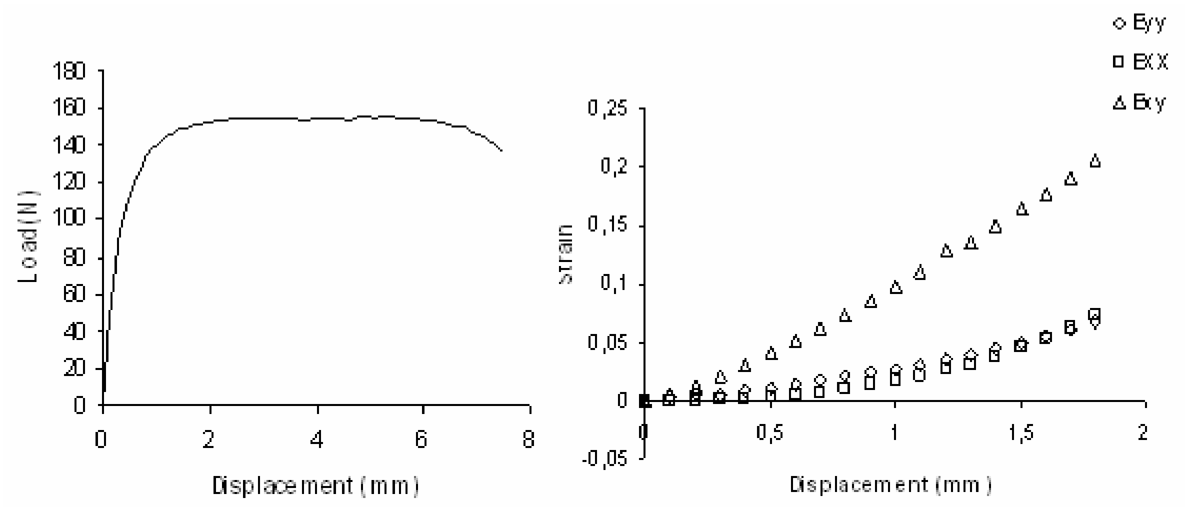



**Figure.7.** Load-displacement response of the butterfly-shaped specimen and strain-displacement obtained from DIC calculation for α = 0°

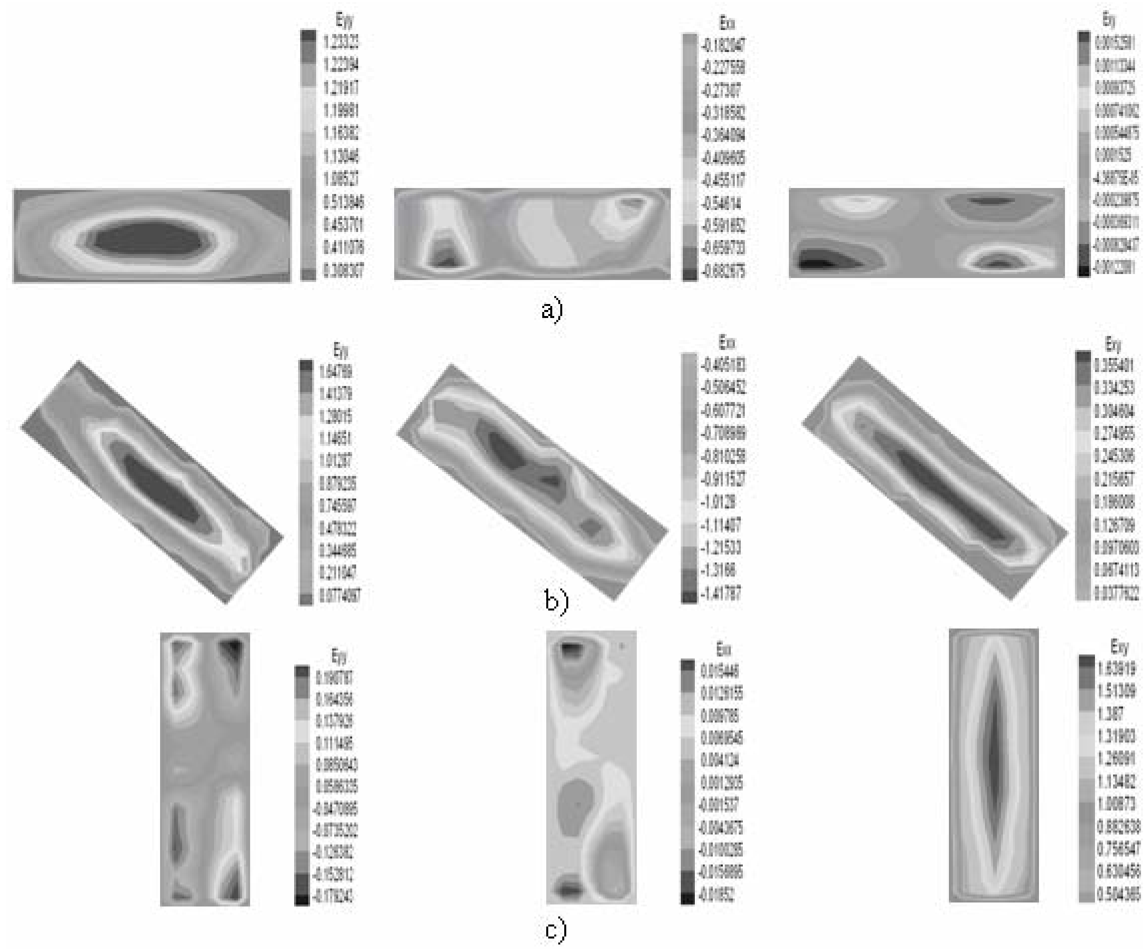



**Figure.8.** Eyy, Exy and Exx strain map in the central section of butterfly-shaped specimens: (a) α = 90°, (b) α = 45°, (c)α = 0°.

## 4 CONCLUSION

The aim of this work was to study the strain field localisation in the central gauge section of the butterfly specimen under biaxial loading. The use of the Arcan apparatus permitted us to conduct biaxial loadings: tensile/shear by changing of the specimen orientation with respect to the loading direction. Digital image correlation technique applied to our experiments permitted us to determine the local strain in the elastic response for tensile, shear and combined tensile shear tests. It also indicates that the strain field is localised in the central area of the butterfly specimen which we have defined by the mask. Al so, the DIC strain results have confirmed the global response of the butterfly specimen under biaxial loading.

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