UDK 532.5:628.1:539.4:678.743 ISSN 1580-2949
Original scientific article/Izvirni znanstveni članek MTAEC9, 45(2)125(2011)

THE IMPACT ON RIGID PVC PIPES: A STUDY OF THE CORRELATION BETWEEN THE LENGTH OF THE CRAZED ZONE AND THE AREA OF THE IMPACTED REGION

UDAR TOGIH PVC-CEVI: ŠTUDIJA KORELACIJE MED DOLŽINO RAZPOKANE ZONE IN POVRŠINO ZONE UDARA

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Prejem rokopisa – received: 2010-07-04; sprejem za objavo – accepted for publication: 2011-01-110

This paper presents a numerical methodology aimed at identifying quantitatively the crazing under quasi-static impact loading of rigid PVC pipes. It also presents the correlation between the length of the crazed region and the area of the impact. Testing low-speed impacts has provided a damaging loading before the rupture of the sample's pipe section. The striker impact on the pipes allows us to appreciate the damage caused. The craze in the impacted area was identified in our previous work [1], the different criteria of the craze initiation are presented. The criterion of Steinstern and Myers, better adapted to rigid PVC [2], is used in a numerical simulation on ANSYS for the problems of static contact. For tests carried out at low velocity, an equivalent static load representing the dynamic impact loading can account for the stress states in the structure of the pipe [3]. The analysis of the stress fields in the structure of the pipe compared to the stress of the craze initiation depends on the first stress invariant and allows us to deduce the length of the crazed region in the thickness of the pipe. Finally, we present the correlation between the length of the crazed region and the area of the zone of impact (the area of the imprint of the striker on the pipe).

Keywords: damage, crazing, impact, PVC, amorphous polymer

Predstavljena sta numerična metodologija za kvantitativno identifikacijo razpokanja pri kvazi statični udarni obremenitvi togih PVC-cevi in korelacija med dolžino z razpokane zone in površino udara. Preizkusni udari z majhno hitrostjo so ustvarili poškodbeno obremenitev pred zlomom prereza cevi. Udarec cevi s kladivom omogoča, da se oceni nastala poškodba. Razpokanje zone udara je identificirano v našem prejšnjem delu [1], zato so predstavljena merila začetka razpokanja. Merilo Steinsteina in Myersa, ki je bolj prilagojen za toge PVC-cevi [2], je uporabljen pri numerični simulaciji ANSYS za problem statičnega stika. Za preizkuse pri majhni hitrosti lahko ekvivalentna statična obremenitev pomeni dinamično obremenitev in omogoči, da se opredeli napetostno stanje v strukturi cevi [3]. Analiza napetostnih polj v strukturi cevi, primerjana z napetostjo začetka razpokanja, je odvisna od invariante prve napetosti in mogoča, da se določi globina dolžine zone razpoke v steni cevi. Končno je predstavljena tudi korelacija med dolžino razpokane zone in površino zone udara (površina odtisa kladiva).

Ključne besede: poškodbe, razpokanje, udar, PVC, amorfni polimer

1 INTRODUCTION

Plastic materials are a large proportion of pipe water-supply systems primarily due to the ease of installation and the relatively low cost of the materials. Plastic pipes used for water canalization continues to be the subject of many studies focusing mainly on the behavioral nature of the material. During construction works, pipes are often subjected to accidental impact such as falling rocks, scratches etc. The ability to resist pressure and the reliability becomes important to engineers. The approach generally used to solve this problem requires the identification and determination of the length of the morphological degradation mechanism of the material during impact.

Amongst the morphological mechanisms identified as responsible for the degradation of amorphous polymers, we find mostly crazes and shear bands [4].

The identification of a craze in the area of the impact has already been demonstrated in a previous study [1]. It is important to define the critical length of the crazed region, beyond which the material can be considered as either obsolete or unusable.

This article focuses mainly on the presentation of a numerical methodology for the determination of the length of a crazed area. A correlation between the area of the impact on the pipe (imprint) and the length of the crazed region is also studied. To illustrate this study, we first define a craze and the different initiation criteria. Subsequently, the material and the dimensions of the test specimens are presented, as well as the experimental impact conditions. Finally, steps in the numerical methodology and the analyses for the determination of the length of the crazed region are exposed.

2 CRAZING

2.1 Presentation

Crazing is a defect resulting in the appearance of cracks on the surface of a material. Crazes are superficially similar to cracking.

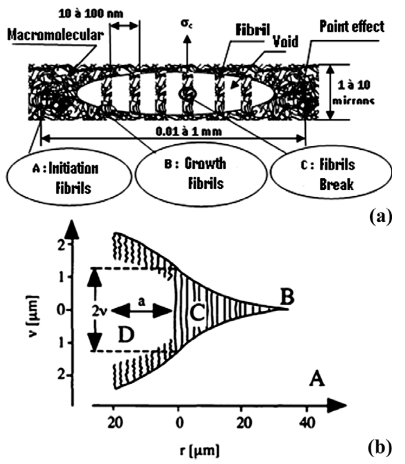

Figure 1: (a) Diagram of a craze with cracks characterized by the presence of fibrils [6] (b) Craze region with the result of fissure formation [7]. Zone A represents the region were the glassy polymer is elastically deformed. B, the area were initiation crazing occurs. C propagation or growth of the crazed region. D Rupture of the fibrils leading to the transformation of the craze into a crack of length a.

Slika 1: (a) Diagram poškovanja, ki ga karakterizirajo fibrili [6]. (b) Zona risov z rezultati nastanka razpok [7]. Zona A je področje, kjer je bil steklast polimer elastično deformiran. B je površina nastanka risov. D je prelom fibrilov, ki rise spremeni v razpoko z dolžino *a*.

However, there are differences between them. Crazes are characterized by crack partitions linked together by small parallel fibrils of the material [5] (see **Figure 1a**).

Crazes and cracks proceed in three stages. Initiation, which is the enlargement and rupture of fibrils. Crazing involves a process of stretching the bulk of the material towards the area were the fibrils are located at the beginning of the crack [8].

2.2 Criteria of craze initiation

In elastic and visco-elastic regimes or after the development of a significant plastic deformation, the corresponding formula of the initiation criteria is distinct for each regime. In a previous publication [1], we detected the first craze in elasto/visco-elastic regime for rigid PVC. The initiation criteria presented below, correspond to the craze appearances in elasto/visco-elasto regimes and elaborate on different phenomenological bases.

Following the observation of an incubation time for the craze formation where the constant stress is less than half of the yield stress (σ_y), Argon et al. [9] proposed a sophisticated formula (1), as shown below

$$\left|\sigma_1 - \sigma_2\right| = \frac{A}{C + 3I_1 / 2\sigma_y Q} \quad (1)$$

where A and C represent material parameters. σ_1 and σ_2, respectively, are the maximum and minimum principal stress. I_1 is the first stress invariant, Q = 0.0133 is a factor controlling the dependency of the criterion to the shear stress on I_1 and σ_y is the yield stress.

Sternstein and Myers [10] proposed a criterion based on the mechanism of micro-void formation in a dilatational stress field, and on the stabilization of micro voids through a deviatoric stress (2). Recently, following the same approach, Gearing [11] proposed a criterion based only on the maximum principal stress (3):

$$\left|\sigma_1 - \sigma_2\right| \geq A^0 + \frac{B^0}{I_1} \quad (2)$$

$$\sigma_1 \geq A + \frac{B}{I_1} \quad (3)$$

With the same idea, Oxborough and Bowden suggested the definition of a criterion based on critical deformation. The criterion has been reformulated in the stress for an elastic material, with ν standing for the Poisson's ratio and E for the Young's modulus ($X' = EX$ and $Y' = EY$ are two material parameters depending on the temperature) (4):

$$\sigma_1 - \nu\sigma_2 - \nu\sigma_3 \geq X' + \frac{Y'}{I_1} \quad (4)$$

To account for the sensitivity to hydrostatic pressure observed for some polymers, Ishikawa [12] proposed the following criterion (5):

$$I_1 \geq A + \frac{B}{I_1} \quad (5)$$

3 EXPERIMENTAL PROGRAM

3.1 Material

The pipes used are mostly made up of polyvinyl chloride (rigid PVC). They come from the same

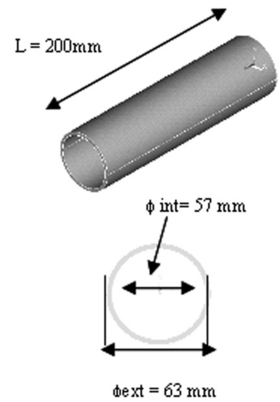

Figure 2: Dimensions (in millimeter) of samples of the test tube for the impact test

Slika 2: Dimenzije vzorcev (v milimetrih) preizkusne cevi za udarne preizkuse

Table 1: Mechanical properties of rigid PVC

Tabela 1: Mehanske lastnosti togega PVC

Properties	**Values**
Young's modulus	3200 MPa
Tensile stress fracture	75 MPa
Elongation at fracture tensile	100 %
Tensile strength in compression	50–75 MPa

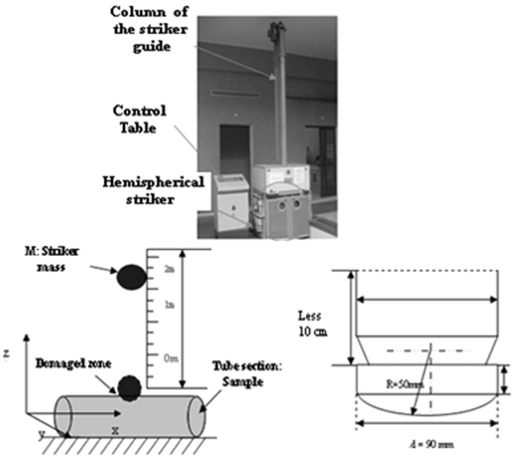

Figure 3: (a) Impact machine from the German TestSystems UTS, (b) synoptic diagram of the impact machine, (c) dimensions of the hemispherical striker

Slika 3: (a) Udarna naprava nemškega proizvajalca TestSystems UTS, (b) sinoptičen diagram udarne naprave, (c) dimenzije hemisferičnega kladiva

molding. The pipe dimensions are 63 mm in diameter and a wall with a 4.5 mm thickness (see **Figure 2**).

3.2 Presentation of the impact machine

This device allows us to drop a weight (striker) from a selected height onto a pipe (see **Figure 3a and 3b**). The section of the pipe is placed on a support "*V*". A cylindrical rigid bar to help prevent the rebound of the striker during and after the impact is introduced. A weight of the striker equal to 16 kg and of radius R = 50 mm is used. (See **Figure 3c**). The height used ranges between 0 m and 2 m. The mass, height and velocity are used to calculate the kinetic energy of the impact.

After impact, the object dropped of mass 16 kg, leaves an elliptical mark called the impacted area or the area of impact at the point of impact (see **Figure 4**).

4 METHODOLOGY FOR DETERMINING THE LENGTH OF THE CRAZED REGION

In a previous publication [1] we have identified the crazing as the morphological mechanism of damage in the impacted area (see **Figure 4**). In this section, we propose a numerical methodology for determining the length of the crazed region in the pipe wall thickness below the impacted area (see **Figure 4**).

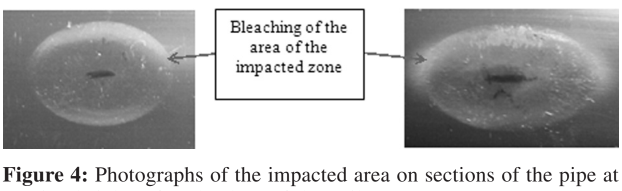

Figure 4: Photographs of the impacted area on sections of the pipe at varying heights after the drop of the striker (mass)

Slika 4: Posnetka površine udara na prerezih cevi po različni višini padca udarnega kladiva

The craze initiating to the critical stress (in agreement with the criterion of craze initiation considered) and the methodology consist of delimiting areas in the pipe were the stress levels are greater than the critical stress ($\sigma \geq \sigma_{cr}^{am}$, σ_{cr}^{am}: critical stress initiation).

The different criteria for the craze initiation presented above (Section1.2) are valid, depending on the type of material. An analysis of these criteria showed that the criterion of Sternstein and Myers (2) is the best adapted for rigid PVC.

The determination the length of the crazed region requires the calculation of stress fields in the wall thickness of the pipe material at the time of impact. These experiments are difficult. We have constructed a numerical model based on Ansys for the simulation of the problem of impact dynamics [13]. As our test impacts are at low velocities (V < 6 m/s), it is shown in the literature that a static equivalence of a dynamic problem is sufficient to account for the stress in the structure [3]. Therefore, the impact of the striker on the pipe is treated as a static contact problem between two solid bodies. The normal load applied on the upper surface of the striker (see **Figure 5**) is obtained through the equations of Hertz, linking the dimensions of the impacted area (see **Figure 4**) to the static normal force. A visco-elastic constitutive law is applied to the numerical model in order to reduce the computation times of the problem, which is already highly non-linear, without altering the objectives of the study. Indeed, the craze initiating for the case of rigid PVC in the elastic regime and the critical stress initiation are expected to lower the yield stress.

The high stress levels in the material (stress greater than the resistance of the material studied) do not affect the final results of the experiment.

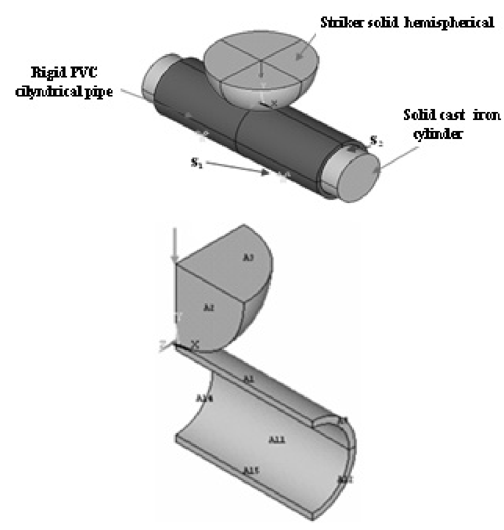

Figure 5: Geometric representation of the numerical model: (a) full actual geometry, (b) ¼ of the geometry implemented due to the symmetry of the problem.

Slika 5: Geometrična slika numeričnega modela: (a) polna realna geometrija, (b) ¼ geometrije, uporabljene zaradi simetrije problema

The tests impacts, being numerous, means that the details of the methodology for determining the length of the crazed region in the pipe wall thickness will be presented for an impact using a striker of mass 16 kg dropped from a height of 1.25 m (designated impact: 1.25 m/16 kg).

$\sigma_{S\&M}$, the stress parameter of the pipe to be found, corresponds to the criterion of Sternstein and Myers (2):

$$\sigma_{S\&M} = \left|\sigma_1 - \sigma_2\right| \geq \sigma_{cr}^{am} = A^0 + \frac{B^0}{I_1} \qquad (6)$$

where $\sigma_1 > \sigma_2 > \sigma_3$, A^0 = 19.936 MPa and B^0 = 1 203.384 MPa 2 for rigid PVC.

Figure 7, represents a cartograph stress state in the wall thickness of the pipe. Around each isovalue of a contour line with the stress represented by we observe that from the given equation above, the critical stress of Sternstein and Myers (σ_{cr}^{am}, see formula (6)) varies weakly with I_1 (see **Figure 6**). Moreover, it seems reasonable that the local critical stress for the craze initiation decreases as I_1 increases. Thus, the creation of micro-voids before crazing would be easier and would lead to a lower stress initiation. This reflects in a decrease in the critical stress while "I_1" increases.

In **Figure 6** we see that the variation of is not very significant and in all cases it does not fluctuate above and below 10 % of its average value. Thus, the critical stress σ_{cr}^{am} at all points on an isovalue contour of the stress '$\sigma_{S\&M}$' is considered constant.

Each isovalue contour of the stress in **Figure 7b** is a possible limit between the crazed regions and others not crazed in the thickness of the pipe. This limit is identified when. We also notice that all the isovalue contours cover the entire section of the thickness of the pipe (see **Figure 7b**). Thus, whatever the limit of the isovalue contour, crazing occupies the entire thickness of the pipe, where the stress fields represent (with being constant on an isovalue contour).

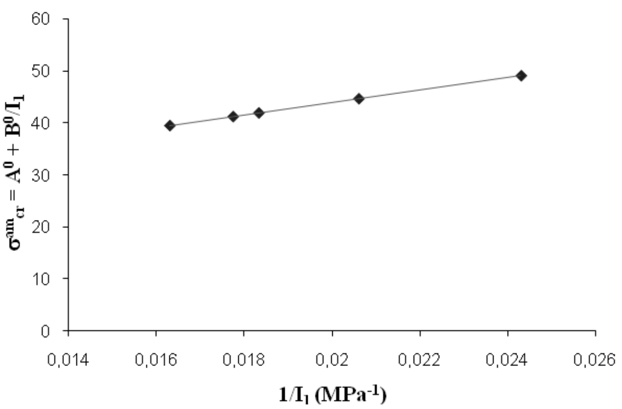

Figure 6: A graph of the critical stress of the craze initiation of the Sternstein and Myers criterion $\sigma_{cr}^{am} = A^0 + B^0/I_1$ around an isovalue contour in the thickness of the pipe.

Slika 6: Graf kritične napetosti začetka poškodbe po Sterstein-Myersovem merilu $\sigma_{cr}^{am} = A^0 + B^0/I_1$ za enake vrednosti po obodu cevi

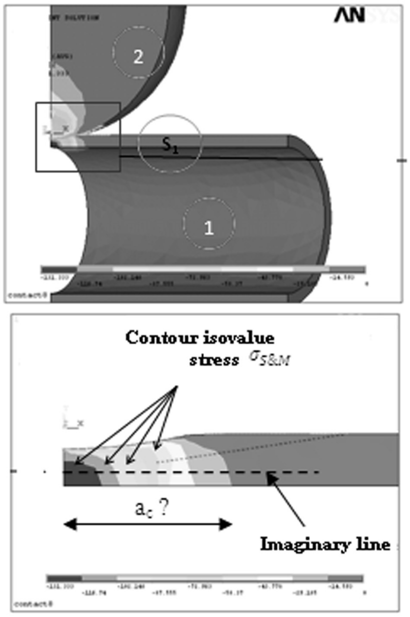

Figure 7: Cartograph of stress states $\sigma_{S\&M} = |\sigma_1 - \sigma_2|$ corresponding to the criterion of Sternstein and Myers. (**a**) ¼ of the geometry of the pipe, (**b**) surface S1 of the thickness of the pipe

Slika 7: Kartografija napetostnega stanja $\sigma_{S\&M} = |\sigma_1 - \sigma_2|$

Considering as a constant on an isovalue contour, the representation of the stress states compared to critical stress initiation along an imaginary line (see **Figure 7b**) is sufficient to determine the length of the crazed region, which corresponds to .

Figure 8, represents the stress states compared to along an imaginary line located at any position, crossing the right section of the structure of the pipe (S_1) just below the contact point (see **Figure 7**).

In **Figure 8**, the intersection between the plot and indicates the limit of the crazed region. Beyond this intersection, the stress is less than the stress initiation. The stress state is abnormally large and the structure can be attributed to the elastic constitutive law applied to the numerical model. Nevertheless, the intersection point is

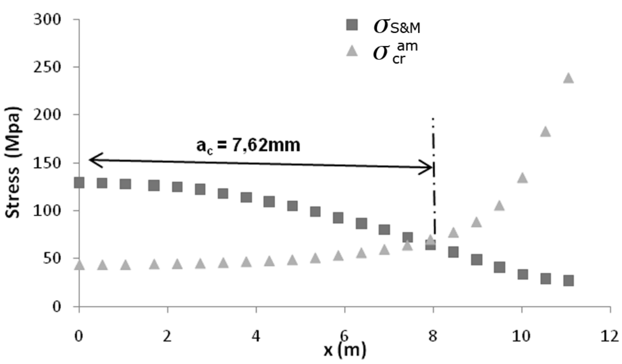

Figure 8: A Graph of the critical stress for craze initiation against the stress state of the material subjected to loading, along an imaginary line selected in the pipe.

Slika 8: Grafikon kritične napetosti za nastanek poškodbe σ_{cr}^{am} proti napetosti $\sigma_{S\&M}$ za obremenjeni material po imaginarni črti v cevi.

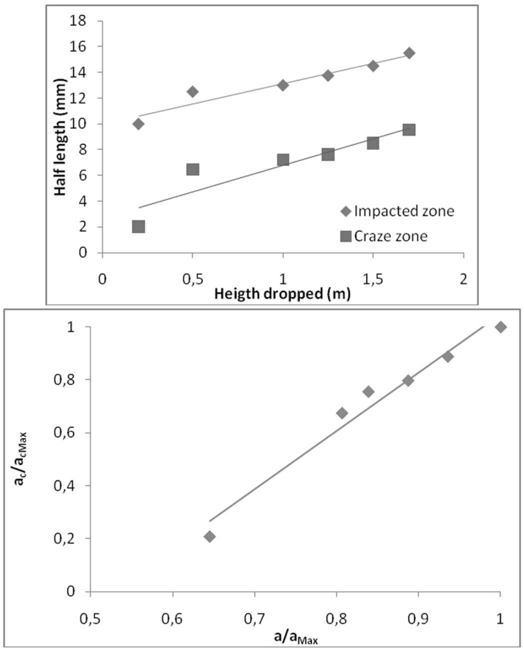

Figure 9: (a) Evolution comparison of crazed region "a_c" and impacted area "a" depending on the level of impact. (b) Evolution of the corresponding non-dimensional "a_c/a_{cMax}" by to "a/a_{max}"

Slika 9: (a) Evolucija primerjanega poškodovanega področja "a_c'" in področja udara v odvisnosti od velikosti udara; (b) ustrezne brezdimenzijske vrednosti "a_c/a_{cmax}" in "a/a_{max}"

where the stress 51 MPa ≤ σ_y = 52 MPa (σ_y: yield strength in tensile of the rigid PVC).

In **Figure 8**, the half-length "a_c" of the crazed region, of the stress state corresponding to the test impact using, respectively, a height and mass of 1.25 m and 16kg is: **7.62 mm** ($a_c = L_c / 2$: half the length of the crazed zone).

Table 2 summarizes the determined size of the half lengths of the crazed regions corresponding to the different impact tests performed ($h \in$ [0.2 m 1.7 m]).

Table 2: Half-length of the crazed region "a_c" corresponding to the impacts of mass 16kg dropped from different heights

Tabela 2: Polovica dolžine poškodovane zone "a_c", ki ustreza udaru mase 16 kg spuščene z različne višine

Designation (m/kg)	h	a/mm	a_c/mm
0.2 m/16 kg	0.2	10	2
0.5 m/16 kg	0.5	12.5	6.45
1 m/16 kg	1	13	7.22
1.25 m/16 kg	1.25	13.75	7.62
1.5 m/16 kg	1.5	14.5	8.49
1.7 m/16 kg	1.7	a_{Max} = 15.5	a_{cMax} = 9.55

From **Table 2**, we notice that the dimensions of the various areas of impact "a" are higher than the corresponding crazed "a_c". It is true that bleaching the impacted area (see **Figure 4a**) allows the localization of the morphological degrading mechanisms (damage caused by the impact).However, it does not help to determine its length. But the developments of these two parameters show correlations (see **Figure 9**).

In the range of the impact tests performed ($h \in$ [0.2 m, 1.7 m]), the evolutions of "a_c" and "a" show an almost linear growth with the level of impact (see **Figure 9a**). In **Figure 9b**, the correlative evolution shows a linear dependence of these two quantities. The area of the imprint (impacted area) may be a good indicator of the length of the crazed region in a pipe subjected to an impact.

5 CONCLUSION

A numerical methodology for determining the length of the crazed region in a rigid PVC pipe subjected to a quasi-static impact has been presented.

With crazing identified on the impacted area [1], determining its length with the methodology proposed involves a comparison of the stress states in the structure for the critical stress of the craze initiation. After choosing the criterion of initiation of Sternstein and Myers (6) for rigid PVC [2] we notice that its dependence on the first stress invariant I_1 induces some distinct critical values. However, on an isovalue contour of stress, the criterion does not deviate more than ±10 % from the average value (see **Figure 6**). From this small variation we considered the value of the critical initiation as a constant on an isovalue contour. Thus, the comparative representation of the stress in the wall thickness of the pipe $\sigma_{S\&M}$ and the critical stress initiation craze σ_{cr}^{am} (see **Figure 8**) along a line crossing all the boundaries of all the isovalue contours (see **Figure 7b**) allow us to deduce the length of the crazed region corresponding to $\sigma_{S\&M} \geq \sigma_{cr}^{am}$. Depending on the level of the impact load, we see a linear growth of the length of the crazed region (see **Figure 9a**), which is linearly correlated to the size of the corresponding impacted area (see **Figure 9b**).

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