



Finite element analysis of cracks in aging aircraft structures with bonded composite-patch repairs

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ABSTRACT

Bonded composite-patch repair has been used to transfer load from cracked structures to the reinforcement such that subsequent crack propagation is reduced. In this study, the mechanical behavior of a single edge v-notch Al7075-T6 plate repaired with 1-ply and 4-ply composite patches was investigated through the finite element method. Contour integral method was used to define and evaluate the stress intensity factors at the crack tip. The effect of the adhesive epoxy film, patch material, thickness and ply orientations on the evolution of the stress intensity factor (SIF) of the repaired structure was examined. The results indicated that the SIF of the notched plate is reduced by 1/6–1/20 as a result of the bonded composite-patch repair. The crack mouth opening displacement (CMOD) is reduced even further by 80–83%. Shear strength and thickness of the adhesive bond were the largest factors in the effectiveness of patch repair.

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1. Introduction

It is economical to use various crack repair techniques to regain the load-carrying capability of cracked components and to extend the service life of aging aircraft, particularly when the crack size is relatively small. The use of bonded composite patches to repair damaged aircraft and marine structures was first initiated by Baker [1]. They have been successfully used on military aircraft for many years due to their high strengths, specific stiffness, longer fatigue life, corrosion and wear resistance [2]. However, as composite patches were bonded to the metallic plate surfaces symmetrically (double patch) or asymmetrically (single patch), the plate would develop highly complicated three-dimensional stresses. Thus, prediction of the behavior of repaired structures remains a challenge under in-plane loading.

Finite element method (FEM) provides a powerful means to conduct virtual experiments and analyze the behavior of the cracked plate under various configurations. It has been one of the most prevalent numerical tools in the field of fracture mechanics since the early 1960s. Researchers have been developing new techniques to improve the accuracy of FEM in application to fracture mechanics [3–11]. The use of quarter point elements in improving the accuracy of the solution around the crack tip was suggested by Henshel and Shaw [12] and Barsoum [13]. Murti et al. [11] took this study further by developing several other element types to

increase the accuracy of the SIF calculation. Megueni et al. [14] used the quarter point element in their finite element model of the cracks repaired with bonded composite patches. They found out that the stress intensity factors are reduced with a thicker patch, thereby reducing the negative effect of disbond. A similar computational study conducted by Umamaheswar and Singh [15] also suggested a direct relationship between the adhesive thickness and reduction in SIF. When SIF is the determinant of the amount of damage, it may lead to structural failure as it grows beyond fracture toughness of the material [16]. Experimental static and fatigue tests conducted by Wang and Pidaparti [17] revealed a 10 fold increase in fatigue life and 2–4 times decrease in stress intensity factor, by repairing an Al7075-T6 pre-cracked specimen with 4-ply boron/epoxy composite patch.

Most of computational models of the composite-patch-repaired plates utilized a simplified two-dimensional model [3,4,8,14]. However a plate under in-plane loading would develop highly complicated three-dimensional stresses if patches are bonded to its surfaces regardless of single or double sided patch. This will become more difficult to predict the behavior of the repaired plate and the subsequent derivation of SIF.

In the present paper, three-dimensional finite element models, with reasonably low aspect ratio elements at the crack tip, has been developed to quantify the performance of pre-cracked Al7075-T6 Single Edge Notch Tension (SENT) specimen repaired with various bonded composite patches. The load transfer mechanisms from the aluminum plate to the patch, the effect of single and double sided repairs, initial crack length, adhesive shear modulus, adhesive thickness, patch material, patch thickness, and fiber

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orientation on the reduction of the SIF and mode I crack opening has been investigated.

2. Geometry and materials

A model of a three-dimensional plate with height $h = 305$ mm, width $w = 51$ mm, thickness $t = 1.6$ mm, a pre-existent crack of length $a = 8$ mm, and crack mouth opening of 0.5 mm was created, as shown in Fig. 1. The adhesive and the patch are denoted using subscripts a and p , respectively. A rectangular patch and adhesive with the dimensions $h_p = h_a = 117$ mm, $w_p = w_a = w = 51$ mm, $t_p = 0.66$ mm, and $t_a = 0.12$ mm has been used. The optimum thickness for a patch was adapted from [18] as

$$E_p t_p = Et \quad (1)$$

where E is the modulus of elasticity of the Al plate, E_p is modulus of elasticity of the composite patch, t is thickness of the plate, and t_p is the thickness of the patch.

The above relation is valid only for pure tension loads. For optimum results, it is suggested to take a patch with dimensions 4–5 times the length of the crack [18]. In this study, the effect of crack length on the crack behavior has been studied by varying the crack length as 9%, 15%, 19%, 29%, 39%, and 49% of the plate width (w). The material properties for the Al7075-T6 plate, FM 73 adhesive, boron/epoxy, and carbon/epoxy pre-preg patches are summarized in Table 1.

3. Finite element model

The complete structure has been meshed using three-dimensional hex-dominated quadratic elements. The crack tip, because of its sharp edge, was modeled separately so as to create quarter point elements, converting the 20 node brick elements into 15 node wedge elements, by moving the mid side nodes to $\frac{1}{4}$ of the element length. The mesh created is shown in Fig. 2. The Al plate is subjected to a uniform linear ramping pressure of 250 MPa on one end while the other end is fixed to zero degrees of freedom, which is done to mimic the specimen under test condition. To ensure there is no relative motion between the plate and the patch, both of them are constrained by tying with the adhesive layer.

ABAQUS/CAE, a commercial nonlinear finite element code developed by SIMULIA Inc., was used to perform the analysis. Contour integral method was used to define the on-set of cracking and was requested as an output parameter to calculate the SIF and J -integral at the crack tip. This method uses domain integral technique to expand the area integral in the two-dimensional case and volume integral in the three-dimensional case [21]. This technique provides a better result if a focused mesh is used at the crack and can even produce accurate results by using a coarse mesh. The variation of different fracture parameters by repairing the pre-cracked Al substrate with single and double sided patches has been investigated.

4. Results and discussions

The SIF analytical solution [22,23] was used to validate our computational results. The mode I SIF for a single edge notch specimen in tension [22] can be calculated by

$$K_I = F(a/w)\sigma\sqrt{\pi a} \quad (2)$$

where σ is the applied nominal stress, a is the edge crack length, and $F(a/w)$ is a dimensionless quantity that depend on the part's geometry, the type of loading and the ratio of crack length to the plate width (a/w), which is obtained from experiments as

$$F(a/w) = 0.265(1 - a/w)^4 + \frac{0.857 + 0.265a/w}{(1 - a/w)^{3/2}} \quad (3)$$

For the adhesive joint, Rose [23] has proposed a model (Eq. (4)) to calculate the mode I SIF of the 2D homogeneous isotropic single sided patch-repaired plate, which was validated experimentally by Muller et al. [24].

$$K_p = \frac{K_I}{1+S} \left[\frac{\Delta}{a+\Delta} \right]^{\frac{1}{2}} \quad (4)$$

where K_p is the mode I SIF of the repaired plate, K_I is mode I SIF of SENT specimen, S is a dimensionless quantity of both modulus of elasticity E and thickness t as $\frac{E_p t_p}{Et}$, and Δ is a size parameter that depends on both material properties (modulus of elasticity E and shear modulus G) and thickness of the patch and plate, which is calculated as

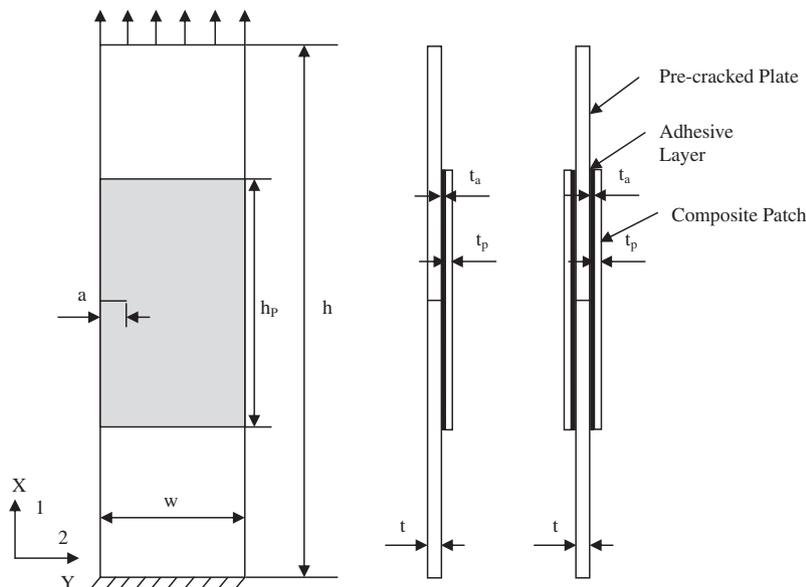


Fig. 1. Geometrical model of the plate with single and double patch.

Table 1
Material properties of cracked substrate, patches and adhesive [17,19,20].

Properties	Al 7075 T6	Boron/epoxy	Carbon/epoxy	FM73 adhesive
Longitudinal modulus, E_1 (GPa)	72	208	145	1.1
Transverse in-plane modulus, E_2 (GPa)	–	25.4	10	–
Transverse out of plane modulus, E_3 (GPa)	–	25.4	10	–
In-plane shear modulus, G_{12} (GPa)	28	7.2	7	0.382
Out of plane shear modulus, G_{13} (GPa)	–	7.2	7	–
Out of plane shear modulus, G_{23} (GPa)	–	4.9	3.7	–
Major in-plane Poisson's ratio, ν_{12}	0.33	0.1677	0.25	0.44
Major out of plane Poisson's ratio, ν_{13}	–	0.1677	0.25	–
Major out of plane Poisson's ratio, ν_{23}	–	0.36	0.5	–
Density (g/cm ³)	2.8	2	1.6	1.2
Yield stress (GPa)	0.49	1.165	–	–
Ultimate strength (GPa)	0.520	1.550	–	0.048

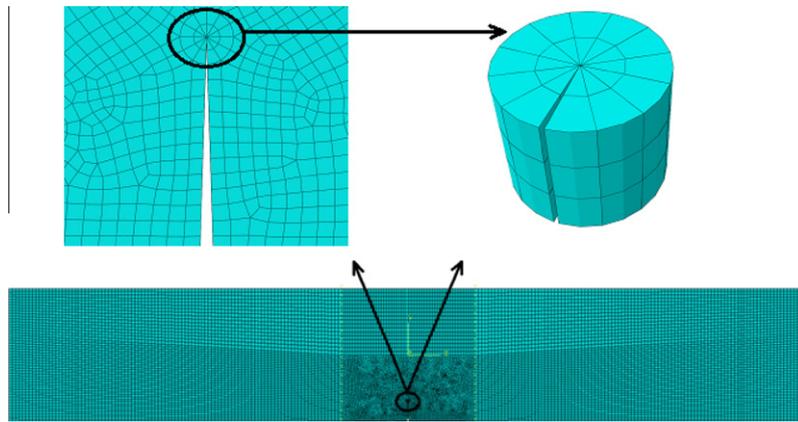


Fig. 2. Finite element mesh.

$$\Delta = \left[\frac{t_a}{G_a} \left(\frac{E_p t_p E t}{E_p t_p + E t} \right) \right]^{\frac{1}{2}} \quad (5)$$

The calculated mode I SIFs are 1616.77 MPa $\sqrt{\text{mm}}$ for the bare plate and 440.88 MPa $\sqrt{\text{mm}}$ for Al plate bonded with single sided patch through a 0.12 mm-thick adhesive layer. The SIF obtained from simulation are 1623.57 MPa $\sqrt{\text{mm}}$ for the bare plate, 446.1 MPa $\sqrt{\text{mm}}$ for the repaired plate with an isotropic patch, It is clear that our SIF computational results agree well with the analytical solutions with a 0.42% deviation for bare plate and 1.2% deviation for repaired plate.

4.1. Effect of single and double sided repair

An un-notched Al plate was modeled first to obtain reference results identified as a baseline. A v-notched plate (bare plate) with an initial crack length $a = 8 \text{ mm}$ or $a/w = 0.156$ was then repaired with 1-ply boron/epoxy patch through single and double sided repairs. Fig. 3 shows a plot of load versus displacement where no strain hardening is specified. The perfect plastic deformation is clearly shown as the yield point is reached. Due to the presence of the crack in the plate, the notched plate has failed earlier before the yield point of the baseline has been reached. With the 1-ply 0° fiber (along the load direction x) direction patch bonded to the notched plate the stiffness of the repaired structure is increased. This thereby decreases the displacement at the point of yield with respect to the un-notched specimen (baseline). The double sided patch repair regains more of the load-carrying capacity than single sided repair.

A displacement profile over the crack is parabolic in nature in the crack tip region and linear away from the crack tip, as shown in Fig. 4. The crack mouth opening displacement (CMOD) in the

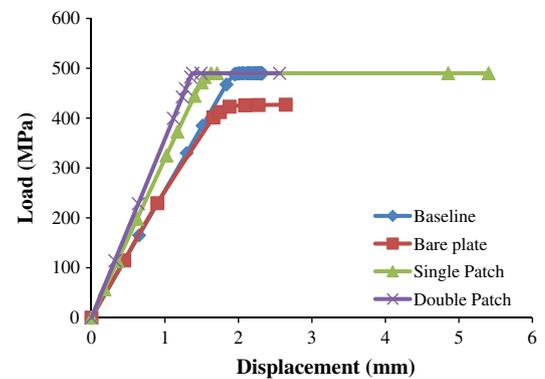


Fig. 3. Regained load-carrying capacity with boron/epoxy patch repair.

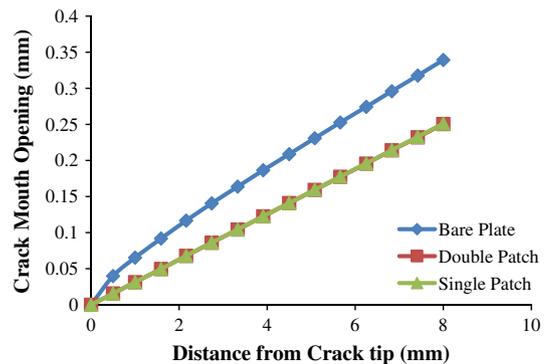


Fig. 4. Crack profile for a plate repaired with boron/epoxy patch.

composite-patch-repaired plate is reduced by 83% of that of the bare plate, even that difference between the single and double patch is in the order of few micrometers. This is due to the dominant stiffness of boron/epoxy patches along the load direction, which is three times of the plate stiffness.

The uniaxial loading leads to a much larger mode I SIF, compared to mode II and III SIF, which could be neglected in this case. The damage of the notched plate will be quantified by mode I SIF only. The reduction in the mode I SIF is around 6–17 times that of a bare plate for single and double sided patch repairs, as shown in Table 2. This indicates that the patch is effective in decelerating the crack growth.

4.2. Effect of initial crack length

Boron/epoxy double patch repair reduces the SIF significantly due to the load-sharing capacity of the composite patch as demonstrated in Fig. 5. The results indicate an asymptotic behavior of SIF as the crack length increases. Additionally, for $a/w = 0.5$ there is 55 times reduction in the SIF for double patch repair with respect to the bare plate.

4.3. Effect of patch material, number of plies, and orientation of plies

Composite patch material plays a vital role in increasing the strength and thereby the service life of the repaired structure. Both the structural material to be repaired and the amount of damage govern the selection of the patch material. In this study, boron/epoxy and carbon/epoxy composite patch materials have been compared for the repair of cracked Al7075-T6 plate.

Fig. 6 and Table 3 demonstrate that the SIF decreased 21% using boron/epoxy instead of carbon/epoxy. It is apparent that boron/epoxy provides better load sharing than carbon/epoxy pre-preg patches. This is due to its better stiffness in the longitudinal direction. There is nearly a three times reduction in the SIF by using a 0° fiber orientation (perpendicular to the advancing crack) rather than a 90° orientation (parallel to the emanating crack) as shown in Table 3.

The number of plies and ply orientation are two different factors which also influence the mechanical properties of the composite. The number of plies to be considered for a composite patch depends on the amount of damage and the ply orientation depends on the direction in which the damage is present, and may subsequently progress, as well as the loading directions [19].

Under the assumption of a constant thickness of the composite patch, the 4-ply boron/epoxy is inferior to the 1-ply patch (Fig. 6). This is due to the fact that the load is uniaxial along the fiber direction of the 1-ply patch. The 4-ply patch will be superior for multi-axial loading conditions. Table 3 clearly shows the increase of the SIF as the ply orientation is changed away from 0° in x -direction. As the ply orientation varies from $0/30/30/0$ to $0/90/90/0$, the SIF increased by 20%. This is because the effective elastic modulus of the composite patch is decreased in the direction perpendicular to the crack thereby increasing the SIF at the crack tip. In summary,

Table 2
Stress intensity factors after composite-patch repair.

Name	Patch material	Averaged mode I stress intensity factor along crack tip (K_I) (MPa $\sqrt{\text{mm}}$)
Cracked bare plate	–	1623.57
Repaired single patch	Boron/epoxy	291.35
Repaired double patch	Boron/epoxy	96.11

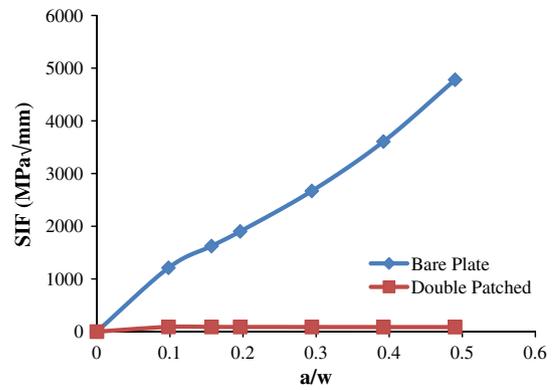


Fig. 5. Effect of crack length on the SIF.

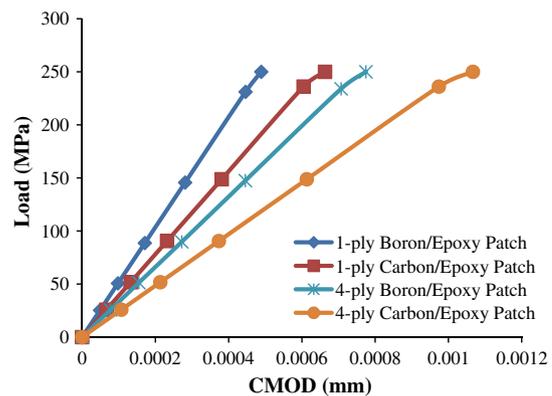


Fig. 6. Effect of patch material and number of plies on the crack behavior.

the effectiveness of the ply orientation depends on the loading direction and the crack direction.

4.4. Effect of a patch thickness

Patch thickness depends on the level of cracking and the thickness of the damaged panel. A series of analysis have been performed by varying the composite patch thickness for a double patch repair as shown in the Fig. 7. It illustrates a considerable reduction in the SIF as the patch thickness increases. This is because that double patch is capturing most of the stresses generated by the crack. Simulation results show that the double patch is supporting 73.4% of the applied load with a patch thickness of 0.6 mm. A thicker patch is desirable; however the bonding efficiency needs to be considered in order to decide an appropriate patch thickness.

4.5. Effect of adhesive shear modulus

The adhesive used plays a significant role in bonding a composite patch to the repaired structure. Its main primary purpose is to transmit the loads to the composite patch. Since the adhesive layer in this work is in shear, adhesive shear modulus is one of the two main parameters which affect the efficiency of an adhesive. It is clear from Fig. 8 that as the adhesive shear modulus increases, there is a drop in the SIF. However, a high shear modulus will cause the higher shear stress to develop in the adhesive or the substrate. This will inherently cause a failure of adhesion (delamination or breakage) because forces are pulling in opposing directions across the adhesive bond [15,19,25].

Table 3
Stress intensity factors for different patch materials, number of plies and their orientation.

Name	Patch material	Ply orientation (with respect to x -direction)	Averaged mode I stress intensity factor along crack tip (K_I) (MPa $\sqrt{\text{mm}}$)
Repaired double patch	1-Ply boron/epoxy	0°	96.11
Repaired double patch	1-Ply boron/epoxy	90°	280.1
Repaired double patch	1-Ply carbon/epoxy	0°	123.02
Repaired double patch	4-Ply boron/epoxy	0/90/90/0	148.42
Repaired double patch	4-Ply carbon/epoxy	0/90/90/0	188
Repaired double patch	4-Ply boron/epoxy	0/30/30/0	123.16

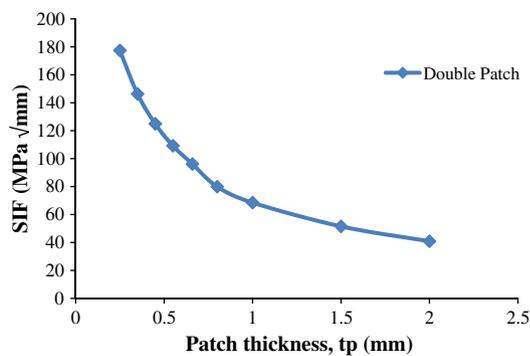


Fig. 7. Influence of patch thickness on SIF.

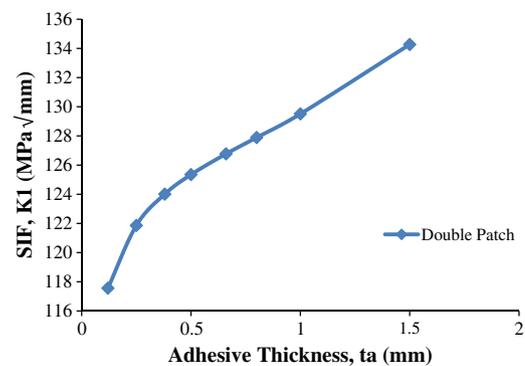


Fig. 9. Influence of adhesive thickness on SIF.

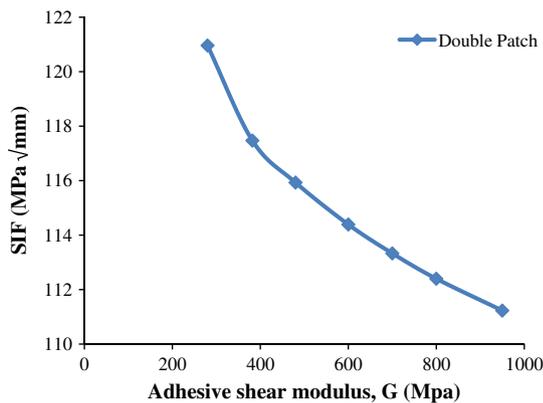


Fig. 8. Influence of adhesive shear modulus (G) on SIF.

4.6. Effect of adhesive thickness

The thickness of an adhesive affects the performance and cost of the bonding. Fig. 9 shows the effect of adhesive thickness on the SIF at the crack tip. There is a considerable increase in the SIF as the thickness of the adhesive increases. This is due to the fact that the adhesive shares more load as the adhesive is thickened. Considering the double patch repair, the adhesive layer with a thickness of 0.12 mm undertook only 0.08% load. The maximum shear stress of 37.52 MPa is located on the edge of the adhesive, and contacted with the plate. When a thicker adhesive of 1.5 mm is applied, it undertook 1.2% load with a maximum shear stress of 14.00 MPa. Arenas et al. [26] also demonstrated that the shear strength is reduced when the adhesive thickness is increased from 0.2 mm to 0.8 mm. In the contrary, if very thin adhesive is applied, then the load transmitting capability will be good but it might fail because of high shear stress. It is advisable to consider an optimal thickness for the adhesive such that neither of the above cases will

occur. The typical structural adhesive thickness used is in the range of 0.2–2.0 mm.

5. Conclusions

Finite element method has been used to study the crack behavior in an Al substrate with composite-patch repair under uniaxial tension. The effect of material and geometrical properties of the patch and adhesive on the fracture behavior of the joint are investigated in this work and summarized as the following:

- By repairing the cracked plate with bonded composite patches on both sides, there is significant reduction in the stress intensity factor at the crack tip, which is also dependent upon the initial crack size.
- Boron/epoxy patches, compared to carbon/epoxy patches, absorb more dissipated energy thereby reducing the stress intensity and crack mouth opening displacement by 20%.
- There is a three fold reduction in the SIF when the ply orientation is normal to the crack emanating direction compared to when it is in parallel to the crack propagation direction.
- The patch thickness has a direct influence on the reduction of the SIF up to a certain point.
- A thinner adhesive with high shear modulus will transmit more of the load to the composite patches and reduce the SIF of the substrate. However, it will be prone to delamination and breakage of the joint.

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