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Effectiveness of Mechanical Treatment of Crack-Arrest Holes Subject to Distortion-Induced Fatigue

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16 Abstract

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An analytical investigation was undertaken in which C(T) specimens were modeled using 3D finite element analysis. The study included the modeled specimens being loaded in Mode I (in-plane loading) and Mode III (out-of-plane loading). In addition to different loading directions, the suite of finite element models included cracks of different lengths, as well as different diameter crack-arrest holes. The models included nonlinear material properties to capture inelastic effects. In some of the models, the crack-arrest holes were subjected to cold expansion and allowed to develop compressive residual stresses.

Stresses around the crack-arrest holes were examined for models with and without the cold expansion treatment. The study clearly showed that while a beneficial influence can be expected from cold expansion for in-plane loading, no such beneficial effect existed for distortion-induced fatigue (out-of-plane loading). Based on these results, the authors concluded that crack-arrest hole treatment can be expected to have limited to no practical benefit when considering cracks caused by distortion-induced fatigue.

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PREFACE

The Kansas Department of Transportation's (KDOT) Kansas Transportation Research and New-Developments (K-TRAN) Research Program funded this research project. It is an ongoing, cooperative and comprehensive research program addressing transportation needs of the state of Kansas utilizing academic and research resources from KDOT, Kansas State University and the University of Kansas. Transportation professionals in KDOT and the universities jointly develop the projects included in the research program.

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Abstract

This report details a study that was aimed at assessing the effectiveness of mechanically treating crack-arrest holes used at the tips of distortion-induced fatigue cracks. Different mechanisms are possible for producing expansion of crack-arrest holes drilled at the tips of fatigue cracks, and such treatments have shown to be effective in improving the fatigue performance of cracks subjected to in-plane loading. However, prior research has not established the effectiveness of crack-arrest hole cold expansion for distortion-induced fatigue applications. Because the majority of fatigue cracks in bridges are caused by distortion-induced fatigue mechanisms, this study aimed to explore whether cold expansion of crack-arrest holes can be expected to produce any benefit to fatigue life.

An analytical investigation was undertaken in which C(T) specimens were modeled using 3D finite element analysis. The study included the modeled specimens being loaded in Mode I (in-plane loading) and Mode III (out-of-plane loading). In addition to different loading directions, the suite of finite element models included cracks of different lengths, as well as different diameter crack-arrest holes. The models included nonlinear material properties to capture inelastic effects. In some of the models, the crack-arrest holes were subjected to cold expansion and allowed to develop compressive residual stresses.

Stresses around the crack-arrest holes were examined for models with and without the cold expansion treatment. The study clearly showed that while a beneficial influence can be expected from cold expansion for in-plane loading, no such beneficial effect existed for distortion-induced fatigue (out-of-plane loading). Based on these results, the authors concluded that crack-arrest hole treatment can be expected to have limited to no practical benefit when considering cracks caused by distortion-induced fatigue.

Acknowledgements

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Chapter 1: Introduction and Background

Fatigue cracking is a major concern for aging steel highway bridges. There are many long-term repair and retrofit techniques for addressing fatigue cracking in steel bridges, but a common first line of defense is to drill crack-arrest holes at the tips of a crack to blunt its fatigue propagation propensity. It is well understood that crack arrest holes are not a panacea for halting crack propagation in steel bridges, and that cracks often reinitiate after additional loading due to a number of reasons—for example, the crack arrest hole may have been too small or the stress range too great. Prior research has shown that there are some possibilities for achieving modest gains in fatigue performance if crack-arrest holes are mechanically treated. One treatment methodology uses a mechanical process to apply plastic deformations to a crack-arrest hole, resulting in a compressive residual stress field that develops around the circumference of the hole. This expansion-based technique has shown to impart a beneficial effect when the fatigue crack and crack-arrest hole are primarily subjected to in-plane loading; however, the influence of such treatment has not been studied for crack arrest holes loaded under distortion-induced fatigue. This paper presents a brief background into the usage of crack-arrest holes to remediate fatigue cracking in steel highway bridges, and an analytical evaluation of mechanically treated crack-arrest holes exposed to both in-plane and out-of-plane loading, to consider the effectiveness of mechanical crack-arrest hole treatment under distortion-induced fatigue loading.

1.1 Fatigue Cracking in Steel Bridges

One of the most persistent problems facing steel bridge owners is the formation and subsequent growth of fatigue cracks (Fisher, 1984), particularly in aging steel bridges. If left untreated, fatigue cracks can propagate to a critical size and potentially compromise the integrity of the entire structure. The majority of cracks in steel highway bridges occur in a structural detail commonly referred to as a *web-gap*, where girder webs intersect with transverse connection plates that are not attached to flanges. The driving force creating cracking in these locations is caused by differential displacements between longitudinal girders and is referred to as distortion-induced fatigue (Hartman et al., 2013; Connor & Fisher, 2006). Due to design requirements and detailing practices of previous eras, older steel bridges in the United States contain details that are highly prone to distortion-induced fatigue cracking (Zhao & Roddis, 2004).

1.2 Distortion-Induced Fatigue

Distortion-induced fatigue cracks are often caused by out-of-plane deformations occurring perpendicular to the web plate where unstiffened gaps were intentionally designed into bridges to avoid fatigue-sensitive weldments. Cracking in these areas has been observed to occur within the first 10 years of service life, with cracks then propagating out of the web-gap region (Fisher & Keating, 1989). Web-gap cracking can originate and grow in a variety of locations and directions, dependent upon detail geometry. Common crack shapes include horizontal cracks occurring along the horizontal stiffener-to-web welds and cracks that initiate at the vertical stiffener-to-web welds and then propagate around the stiffener into a horseshoe shape (Roddis & Zhao, 2001; Liu et al., 2018). Fatigue cracks can also propagate away from connector plates into the web plates, and commonly bifurcate, resulting in a complex combination of vertical, horizontal, and diagonal cracks. The combination of out-of-plane loading and complex geometry causes mixed-mode cracking, primarily driven by Mode I and Mode III.

Bridge owners employ a variety of crack halting techniques in attempts to retard crack growth. Repair and retrofit strategies often attempt to reduce the driving force, stiffen the web-gap region, or soften the susceptible region to allow for differential movement. Methods for dealing with fatigue cracks on bridges include hole drilling, diaphragm and cross-frame removal, diaphragm repositioning, bolt loosening, and web-gap stiffening retrofits (Dexter & Ocel, 2013). Due to ease of application and their perceived effectiveness, drilling crack-arrest holes is typically the first approach taken when bridge owners deal with fatigue cracks.

1.3 Crack-Arrest Holes

Crack-arrest holes utilize fracture mechanics concepts to reduce crack driving force, arresting crack growth. Fatigue cracks are fundamentally characterized as having an idealized, infinitely sharp crack tip with a crack tip radius of zero. Stress intensity, the linear-elastic parameter defining the crack driving force, is known to be inversely proportional to crack tip radius. Therefore, drilling a large-diameter hole at the end of a crack increases the crack tip radius, greatly decreasing the applied stress intensity, theoretically halting further crack propagation. The Federal Highway Administration (FHWA) provides guidelines on the use of hole drilling as a repair method for fatigue cracks in the *Manual for Repair and Retrofit of Fatigue Cracks in Steel Bridges* (Dexter & Ocel, 2013). A sufficiently large diameter is needed to successfully arrest a crack, and larger holes are generally preferred as long as strength and stiffness of the structure or connection are not compromised. Commonly used hole diameters range from 25.4 to 101.6 mm (1.0 to 4.0 in.). However, the manual notes that crack-arrest holes may not be effective at arresting fatigue cracks loaded out-of-plane. Early research showed that crack-arrest holes are effective for in-plane bending stresses less than 42 MPa (6 ksi) and out-of-plane stresses less than 105 MPa (15 ksi) (Fisher et al., 1990). However, a more recent study with nuanced findings performed by Liu et al. (2018) showed that crack arrest hole placement (location) is a more important predictor of crack reinitiation for out-of-plane fatigue than diameter. Overall, the study performed by Liu et al. (2018) indicated that crack arrest holes are not very effective for halting fatigue crack growth under out-of-plane loading conditions. This conclusion is corroborated by decades of physical evidence in the field, where it is a common sight to observe crack-arrest holes drilled multiple times in the same location, as previous attempts to stop crack propagation proved unsuccessful, resulting in an unsightly condition commonly referred to as the “Swiss cheese” effect.

1.4 Mechanical Treatment of Crack-Arrest Holes

For many years, the aerospace industry has treated crack-arrest holes in aluminum structures by mechanically expanding them to lock-in a state of compressive stress around the hole, inhibiting crack reinitiation through the crack-arrest hole. This cold compression can simply be performed by driving an oversized mandrel through a drilled hole, or by use of specialized, commercially available equipment. The large compression field induced around the hole has been shown capable of reducing crack reinitiation propensity for in-plane loading in structural steel applications (Crain, 2010; Crain et al., 2010; Simmons et al., 2014; Simmons, 2013). However, the effectiveness of mechanically treated crack-arrest holes experiencing out-of-plane loading is not well understood.

1.5 Objective

The objective of this study was to analytically evaluate the effectiveness of mechanically treated crack-arrest holes subjected to out-of-plane fatigue loading. A modified compact (C(T)) specimen was evaluated in a suite of finite element models that included nonlinear material properties and was loaded at various levels for both Mode I (opening) and Mode III (out-of-plane shear) loading. A range of crack-arrest hole diameters were included in the suite of models, and specimens were evaluated in both the treated and untreated condition.

Chapter 2: Methods

2.1 Finite Element Models

Finite element models were generated and analyzed with Abaqus/CAE (DSS, 2016). All analyses were performed with identical material properties and the same basic specimen geometry, with variations in crack-arrest hole diameter. Eight-node brick elements (C3D8) were utilized in the models. Mesh density was determined through two mesh sensitivity analyses: the first focused on the area around the crack-arrest holes and examined changes as compressive residual stresses were induced, while the other focused on more global behavior during applied loading.

2.1.1 Specimen Geometry and Material Properties

Specimen geometry was adapted from recommendations presented in ASTM E1921 (2019). A C(T) specimen was chosen, allowing for verification of model accuracy through the application of closed-form stress intensity factor solutions. The thickness of the specimen was 12.7 mm (0.5 in.), representing a realistic girder web plate. The overall size of the model was determined by examining stresses under applied load for a 101.6 mm (4.0 in.) crack-arrest hole. At a width of 508 mm (20 in.), measured from loading pins to the back of the specimen, edge effects did not influence behavior around the hole. Other specimen dimensions including the height of 406 mm (16 in.) and the loading pin diameter of 50.8 mm (2.0 in.) were scaled appropriately based on specimen width.

An initial crack length of 254 mm (10 in.) resulted in a specimen length-to-width ratio of 0.5. Based on hole sizes commonly used on highway bridges and on values used in commercial mechanical treatment equipment, crack-arrest hole diameters were varied between 6.35 mm (0.25 in.) and 101.6 mm (4.0 in.). Hole diameters were examined in 6.35 mm (0.25 in.) increments up to 25.4 mm (1.0 in.), and beyond that in increments of 25.4 mm (1.0 in.). Crack-arrest holes were placed at the end of the crack tip, effectively increasing the crack length by the hole diameter. Although this produced in each model a different crack length and remaining ligament, it accurately represents how the crack-arrest holes are placed in practice.

As most U.S. bridges experiencing distortion-induced fatigue were fabricated with A36 steel, this material was chosen for the study. Non-linear material behavior, including strain hardening, was modeled through the use of the Ramberg-Osgood relationship. Yield and ultimate tensile strengths of 248 MPa (36 ksi) and 400 MPa (58 ksi) were used, along with a modulus of elasticity of 200 GPa (29,000 ksi), shear modulus of 79.3 GPa (11,500 ksi), and Poisson's ratio of 0.3.

2.2 Loading Protocol

Loading for the analyses were based on applied Mode I stress intensity values of 22 and 55 MPa√m (20 and 50 ksi√in.) for the given specimen geometry and crack configuration with no crack-arrest hole. Loads were then held constants for all models, regardless of crack-arrest hole diameter. For Mode III loading, an equivalent driving force was calculated using Equation 2.1, allowing for direct comparison between in-plane and out-of-plane models.

$$\Delta K_I^2 \frac{(1-v^2)}{E} = \frac{1}{2G} \Delta K_{III}^2 \qquad \textbf{Equation 2.1}$$

Equivalent Mode III stress intensities were found to be 18.4 MPa√m (16.8 ksi√in.) and 46.2 MPa√m (42.1 ksi√in.). Out-of-plane loads corresponding to these stress intensity values were used for each model. Additional load levels corresponding to 11, 33, and 44 MPa√m (10, 30, and 40 ksi√in.) were evaluated for the in-plane, Mode I models. Displacement of representative models with a 25.4 mm (1.0 in.) crack-arrest holes are presented for Mode I and Mode III loading in Figure 2.1.

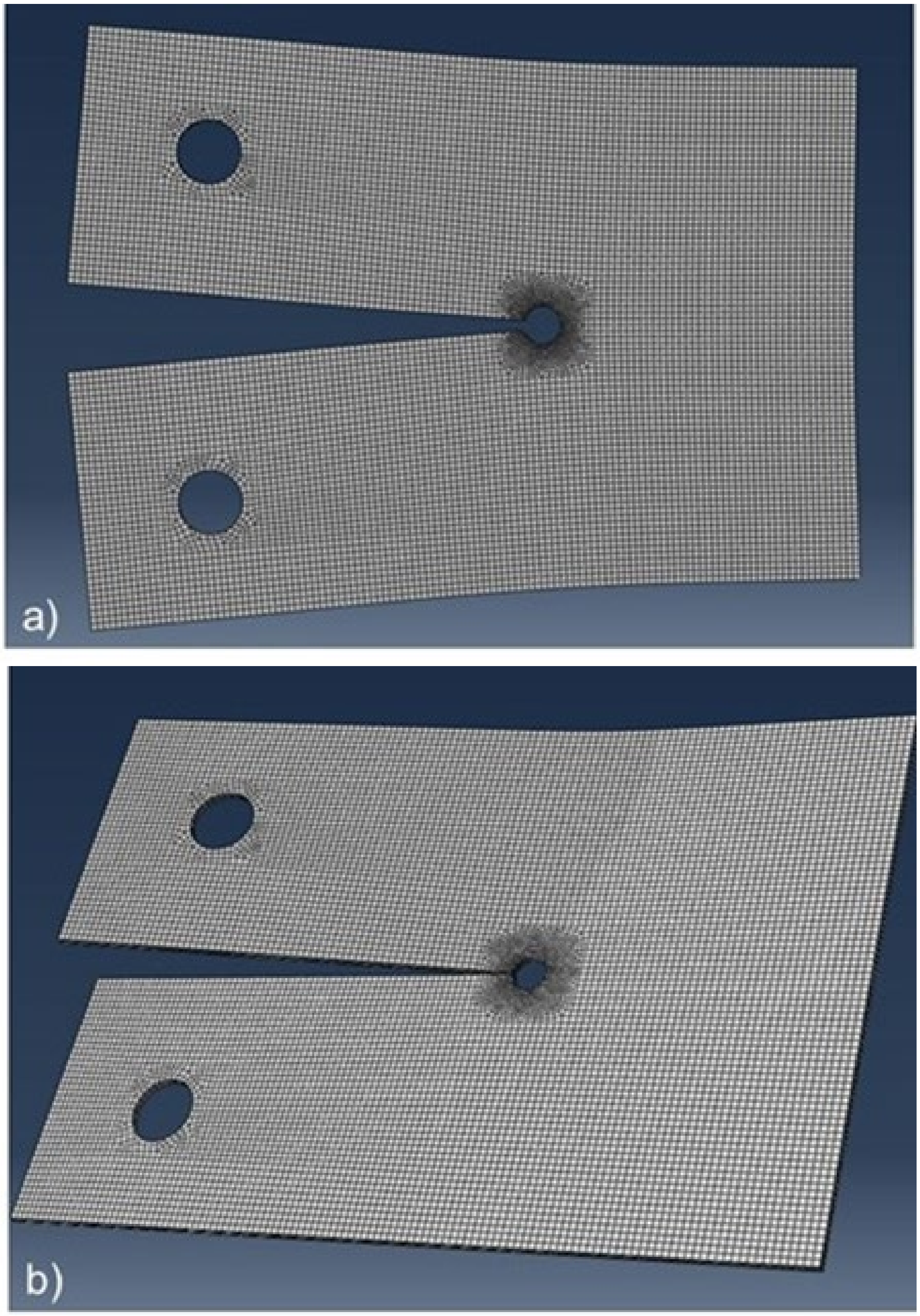

Figure 2.1: FEA model with 25.4 mm (1 in.) diameter crack-arrest hole loaded in a) Mode I, in-plane opening, and b) Mode III, out-of-plane shear

2.3 Mechanical Treatment of Crack-Arrest Holes

To model the cold expansion for the mechanically treated arrest holes, a radial displacement was applied to the holes and then released, producing plastic deformation and residual compressive stresses. Values of expansion for diameters up to 25.4 mm (1.0 in.) were based on expansion values applied with commercially available systems. For holes with diameters larger than 25.4 mm (1.0 in.), relative expansion was held constant. Relative expansion is expressed as a percentage of the difference between final hole diameter minus initial diameter, divided by initial diameter. Values of initial diameter, final diameter, and relative expansion are presented in Table 2.1.

Table 2.1: Mechanically treated crack-arrest hole details

Initial Hole Diameter, mm (in.)	Final Hole Diameter, mm (in.)	Relative Expansion, %
6.35 (0.25)	6.40 (0.252)	0.80
12.70 (0.5)	12.75 (0.502)	0.40
19.05 (0.75)	19.11 (0.7525)	0.33
25.40 (1.0)	25.48 (1.003)	0.30
50.80 (2.0)	50.95 (2.006)	0.30
76.20 (3.0)	76.43 (3.009)	0.30
101.6 (4.0)	101.90 (4.012)	0.30

2.4 Data Collection and Evaluation

Effectiveness of the crack-arrest holes was examined using stresses from the FEA models. Stresses were extracted along a path extending from the edge of the holes to the end of the specimen, in line with the initial crack. Critical Mode I stresses are those acting tangent to the crack-arrest holes, while shear stresses are critical for the Mode III loading condition. Therefore, tangential stress, σ_{yy}, was evaluated for in-plane loading, and shear stress, τ_{yz}, was evaluated for out-of-plane loading. All stresses were extracted from specimen mid-thickness, as these were the highest for all models.

Chapter 3: Results

Results of the analytical evaluation are presented below. The effectiveness of varying diameter crack-arrest holes is evaluated for both in-plane and out-of-plane loading. Following the application of cold expansion to the crack-arrest holes, stresses are again evaluated with no externally applied loads. Mode I and Mode III loads are then applied to the specimen, and resulting stresses are presented.

3.1 Crack-Arrest Hole Evaluation

Presented in Figure 3.1 are tangential and shear stresses for each crack-arrest hole diameter under applied loads associated with 22 MPa√m (20 ksi√in.) and 18.4 MPa√m (16.8 ksi√in.) for Mode I and Mode III loading, respectively. Behavior is typical, and similar results were produced for the 55 MPa√m (50 ksi√in.) and 46.2 MPa√m (42.1 ksi√in.) load cases. It can be seen that in-plane loading produces large tangential stresses away from the edge of the hole, while shear stresses induced by out-of-plane loading are much concentrated at the hole edge. These localized shear stresses are also evident when examining results graphically. Figure 3.2 presents stresses around a 25.4 mm (1.0 in.) crack-arrest hole, taken at specimen mid-thickness, for both in-plane and out-of-plane loading.

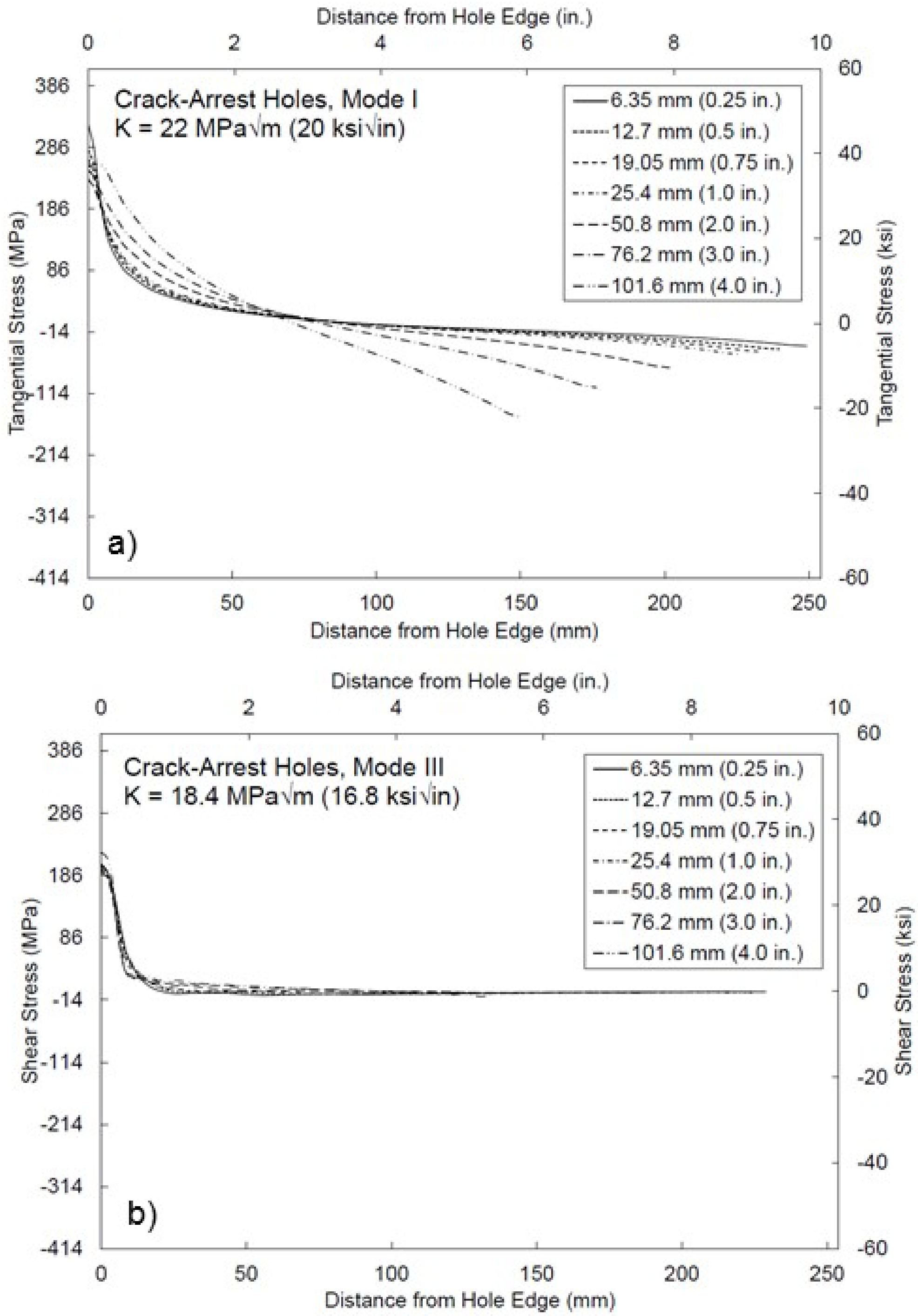

Figure 3.1: Crack-arrest hole a) Mode I in-plane tangential stresses and b) Mode III out-of-plane shear stresses

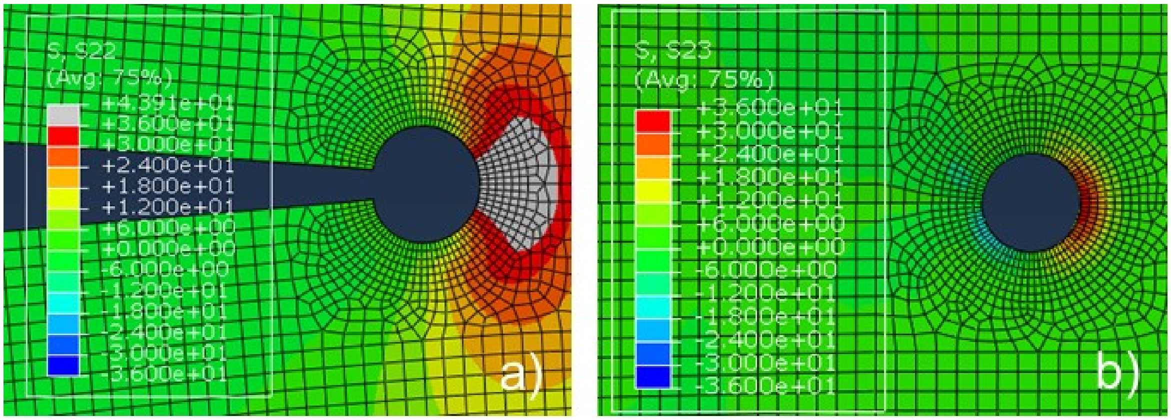

Figure 3.2: 25.4 mm (1 in.) diameter crack-arrest hole: a) tangential stresses for Mode I loaded and b) shear stress for Mode III loading

3.2 Application of Compressive Residual Stresses

Radial displacements were applied around each crack-arrest hole, as described above. This process induced large compressive stresses at the edge of the hole. Tangential stresses produced by the process are seen in Figure 3.3 for each hole diameter. These tangential compressive residual stresses are shown at specimen mid-thickness in Figure 3.4a. Compressive stresses are only created on one side of the hole, as displacements simply cause the crack to open on the opposite side. Only tangential stress is plotted in Figure 3.3 because the cold expansion process does not produce shear stresses in the specimen. This can be seen in Figure 3.4b.

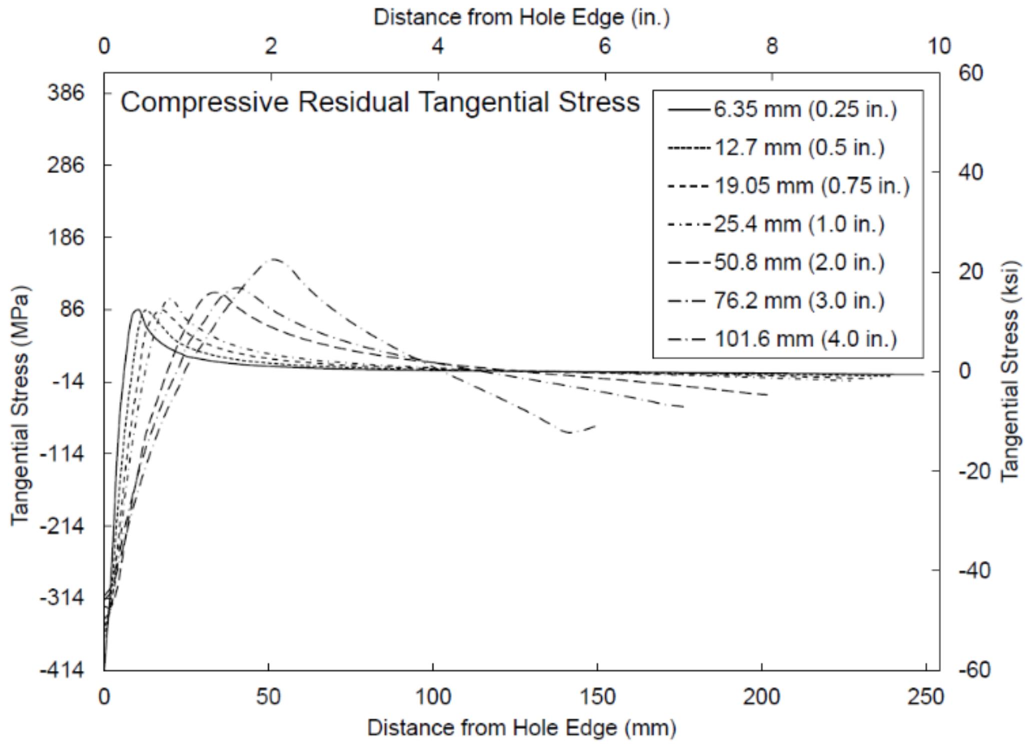

Figure 3.3: Compressive residual tangential stresses

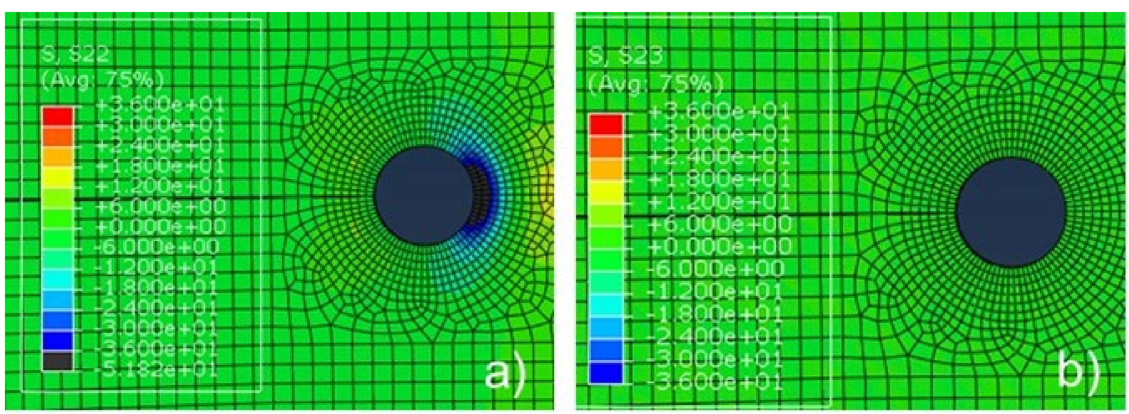

Figure 3.4: Compressive residual a) tangential stress b) shear stress

3.3 Performance of Mechanically Treated Holes

After compressive residual stresses were induced around the crack-arrest holes, the models were evaluated for both in-plane and out-of-plane loading. Tangential and shear stresses for loads associated with 22 MPa√m (20 ksi√in.) and 18.4 MPa√m (16.8 ksi√in.) are presented in Figure 3.5. The performance of these mechanically treated crack-arrest holes can be compared with the behavior of non-treated holes, presented in Figure 3.1. When comparing Figure 3.1a with Figure

3.5a, the tangential stresses at the edge of the crack-arrest hole are reduced significantly with the introduction of cold expansion. Although large tangential stresses still exist, they are removed from the edge of the hole, where the potential for crack re-initiation is the greatest. The induced compressive residual stresses have almost no influence on shear stresses, however, as can be seen in Figure 3.5b.

Although cold expansion of the crack-arrest holes reduced in-plane stresses at the hole edge for the 22 MPa√m (20 ksi√in.) load case, higher loads were able to overcome any induced compression. In addition to the 22 and 55 MPa√m (20 and 50 ksi√in.) load cases, Mode I loading was also examined at 11, 33, and 44 MPa√m (10, 30, and 40 ksi√in.). Resulting stress values for the 25.4 mm (1.0 in.) diameter crack-arrest hole are presented in Figure 3.6. It can be seen that the effectiveness of mechanically treated crack-arrest holes is reduced as load is increased, with any benefit being completely overcome at the 55 MPa√m (50 ksi√in.) load case.

The efficacy of mechanically treating crack-arrest holes can be examined by evaluating stresses at the hole edge, where fatigue cracks would potentially re-initiate. The ratio of treated to untreated hole edge stresses for all load cases, loading modes, and hole diameters is presented in Figure 3.7. This calculation is made with tangential stresses for in-plane loading and shear stresses for out-of-plane loading. Open symbols represent Mode I, in-plane loading, and solid symbols represent Mode III, out-of-plane loading. Values less than unity represent a reduction in hole edge stress, indicating the cold expansion was beneficial as compared to untreated crack-arrest holes. Negative values indicate the applied load was unable to overcome the compression induced by cold expansion.

For Mode I, loads corresponding to 11 and 22 MPa√m (10 and 20 ksi√in.) did not overcome the compressive residual stresses at the edge of the hole, and mechanical treatment reduced stresses for all but the 55 MPa√m (50 ksi√in.) load case. For out-of-plane, Mode III, loading, the case most closely corresponding to distortion-induced fatigue on highway bridges, no reduction in stress was observed for either the of the applied load cases. Hole diameter had little effect on the performance of mechanically treated crack-arrest holes. For the Mode I cases where cold expansion was effective at reducing stress, the benefit peaks at a hole diameter of 50.8 mm (2.0 in.). However, this effect is small compared to that of the applied load, and diameter seems to have no influence on Mode III behavior.

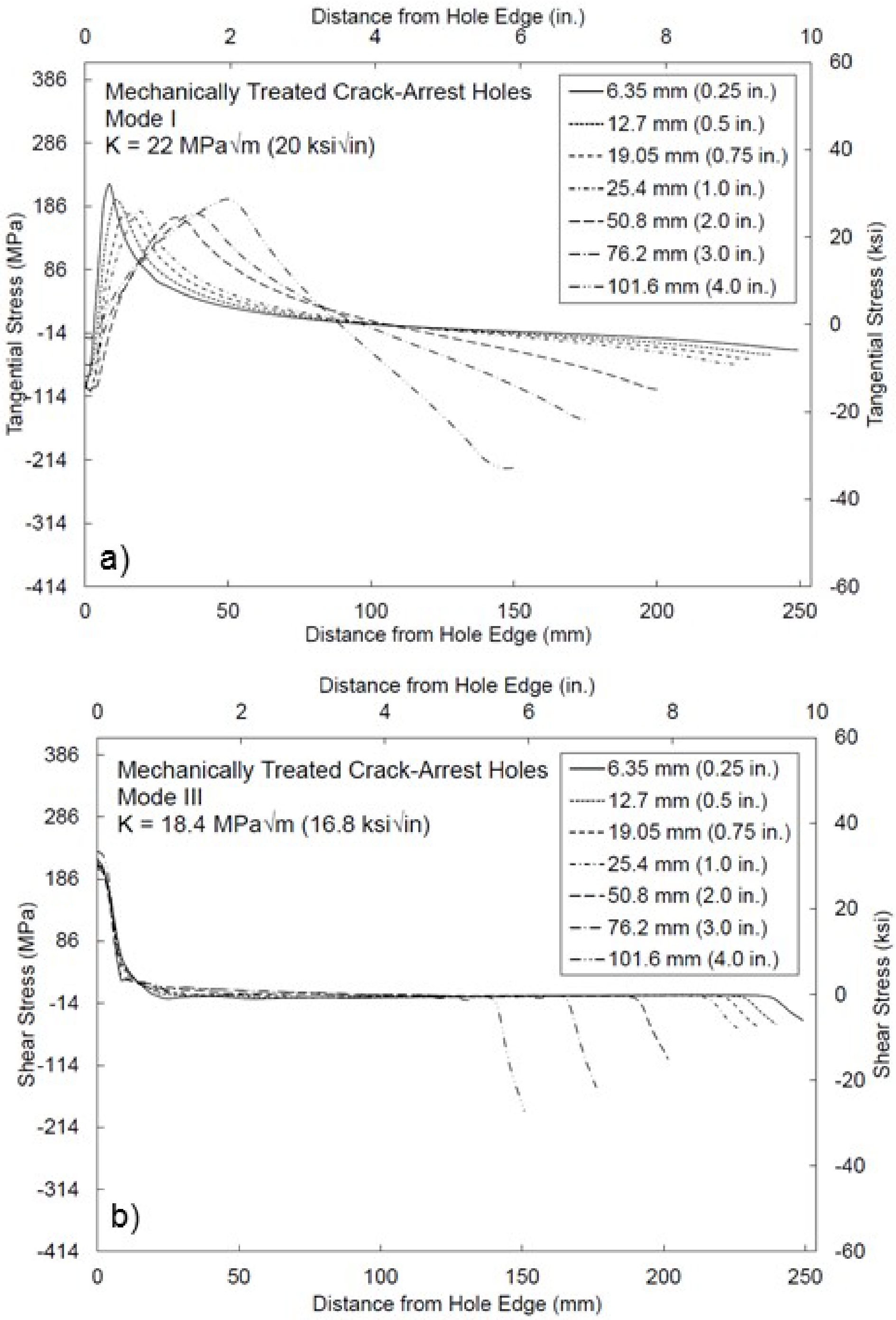

Figure 3.5: Mechanically treated crack-arrest hole a) Mode I in-plane tangential stresses and b) Mode III out-of-plane shear stresses

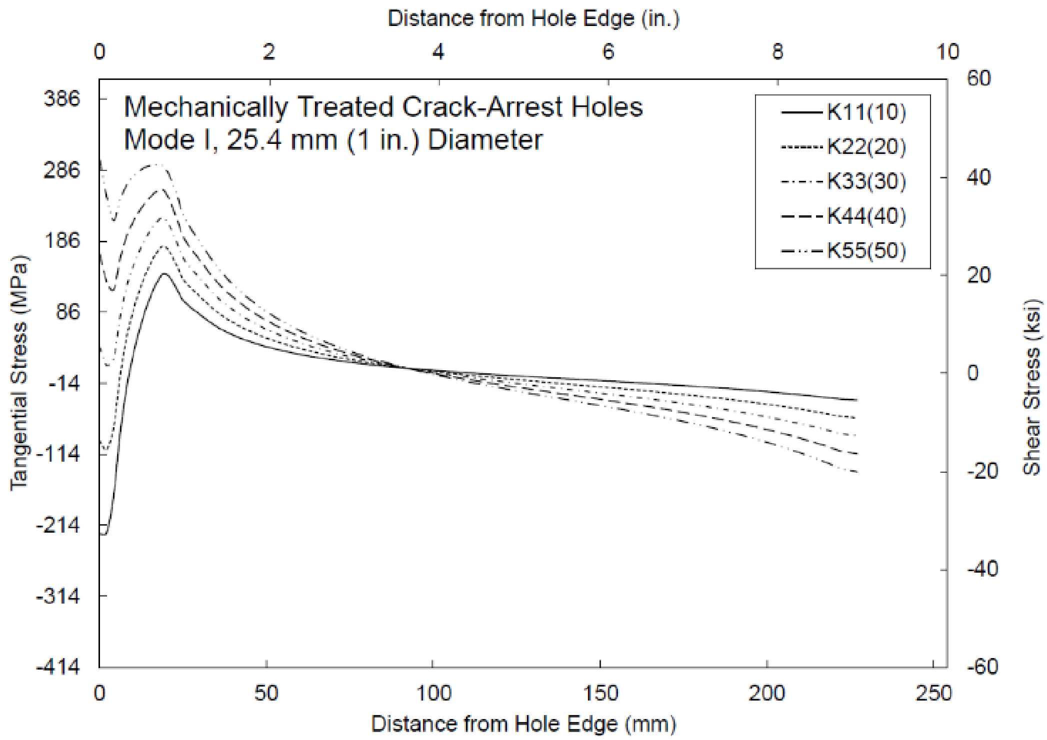

Figure 3.6: Tangential stresses for Mode I 25.4 mm (1 in.) mechanically treated crack-arrest hole

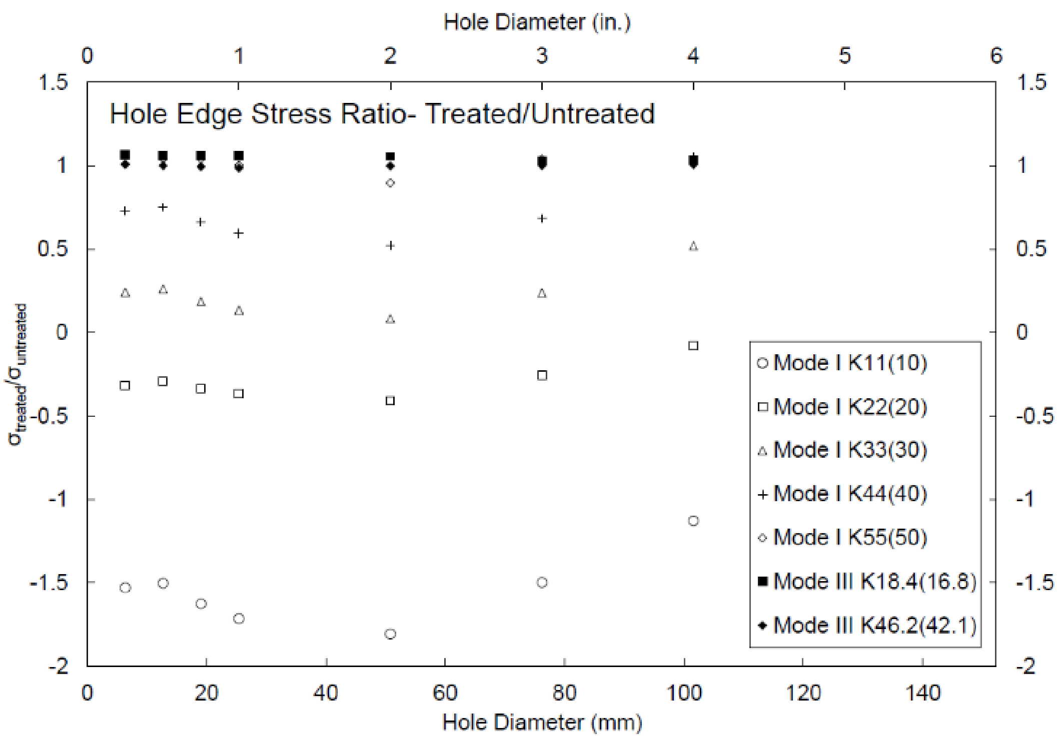

Figure 3.7: Ratio of treated to untreated crack-arrest hole edge stress

Chapter 4: Conclusions and Recommendations

4.1 Conclusions

Analytical models were used to evaluate the effectiveness of cold expansion on fatigue crack-arrest holes. Mechanically inducing plastic deformation of crack-arrest holes was shown to be effective at reducing hole edge tangential stresses for the majority of Mode I, in-plane, loading cases. Extremely high loads corresponding to 55 MPa√m (50 ksi√in.) were able to overcome the residual stresses. It should be noted, however, that loads of this magnitude are unlikely to routinely occur on in-service highway bridges.

Mechanical treatment of the crack-arrest holes was analytically shown to have no influence on hole edge shear stresses induced in Mode III, out-of-plane loading. No shear stresses were induced during the modeled cold expansion process, and shear stresses due to applied out-of-plane loading showed no reduction compared with bare crack-arrest holes. As Mode III out-of-plane shear is a primary driving force for distortion-induced fatigue, the results indicate mechanically treated crack-arrest holes provide no benefit for the majority of fatigue cracking found on steel highway bridges.

Based on the results of this study, use of mechanical treatments for crack-arrest holes is not recommended for distortion-induced fatigue cracks, as they can be expected to be ineffective in slowing or halting crack re-initiation and propagation.

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