Development of a Technique to Improve Fatigue Lives of Crack-Stop Holes in Steel Bridges

Josh S. Crain, Gary G. Simmons, Caroline R. Bennett,
Ron Barrett-Gonzalez, Adolfo B. Matamoros, and Stanley T. Rolfe

A common technique to prevent the propagation of fatigue cracks in bridge girders is to drill crack-stop holes at crack tips. Stress concentrations at the crack tips are reduced and fatigue life of the bridge is extended. The size of the crack-stop hole needed to prevent further crack growth is determined by using known material properties and relationships developed through experimentation. However, these equations often result in a crack-stop hole diameter larger than can be practically drilled; physical limitations force crack-stop holes to be undersized in the field. To improve effectiveness of undersized holes to that of full-sized holes, a method is needed to strengthen undersized crack-stop holes. This study investigated the potential of a technique to improve the fatigue life of undersized, crack-stop holes. It uses piezoelectric actuators operated at ultrasonic frequencies to convert electrical signals into mechanical work. The technique produced residual compressive stresses of the same order of magnitude as those produced by static cold expansion. A suite of finite element models was created to quantify and characterize the residual stresses surrounding the cold-expanded, undersized, crack-stop holes. Results were compared with analyses in the literature.

As a result of the relatively long propagation life between initiation of a fatigue crack and eventual failure, measures can be taken to retrofit and preserve existing cracked bridge members if fatigue cracks are detected early. Several existing methods can retard or stop the propagation of fatigue cracks. These methods include repair welding or grinding of shallow cracks, metal reinforcements, adhesive carbon fiber reinforced polymer patching, altering connection details, and drilling stop holes at crack tips (*1–5*). The methods are attractive considering that the alternatives are to replace the cracked structural member or reduce external loads coupled with careful monitoring.

The technique of drilling a hole at a crack tip is a well-known procedure used in everyday practice to enhance fatigue life of steel structures (*2*). The primary challenges associated with correctly applying this technique are that the theoretical size of the crack-stop hole is often too large for practical implementation in the field or the location is blocked by other members. To overcome these issues, crack-stop holes are often drilled undersized and left unreinforced. While undersized holes do improve fatigue life of a cracked structural member, it has been shown that various levels of cold expansion can increase fatigue life of an unreinforced crack-stop hole by an order of magnitude (*6–14*). The increase in fatigue life provided by cold expansion is a result of the three principal residual stresses induced by cold expansion: tangential, radial, and transverse. Among them, compressive tangential stress (also referred to as hoop or circumferential stress) is the major contributor to significant gains in fatigue life (*9*).

Several techniques have been developed to cold-expand holes in metal structures, each having the common feature of inducing a layer of residual compressive stress around the outside of the hole. These compressive residual stresses are the direct result of forced, inelastic deformation of material around the circumference of a crack-stop hole. As a crack-stop hole is forced to expand through a mechanical process, yielding first initiates along the edges of the hole where stresses are highest. As further expansion is mechanically induced, the zone of plasticity spreads outward from the hole. Material beyond this plastically deformed region deforms elastically under applied stress. After the mechanically applied pressure or displacement is removed from the system, residual compressive stresses around the hole are created from the elastic rebounding, or "springback," of the unyielded material surrounding the permanently deformed plastic zone (*15*). Figure 1 shows the level of residual tangential compressive stress that can be expected to develop around a mechanically expanded hole.

A different technique, examined by Reemsnyder, involved the installation of high-strength bolts in crack-stop holes used to enhance fatigue performance (*16*). While the main focus of the study by Reemsnyder was the potential fatigue life improvement of previously cracked holes in riveted bridge connections, the study mentioned that high-strength bolts were installed in drilled crack-stop holes located a predetermined distance from the riveted connections (*16*). Cracks did not reinitiate from the crack-stop holes with the installed high-strength bolts; however, because fatigue life improvement of crack-stop holes was not the main focus of the study, no quantified fatigue life improvement was provided.

In separate studies performed by Huhn and Valtinat (*17*) and Brown et al. (*18*), the influence of fully tensioned high-strength bolts on the fatigue life of bolt holes in slip critical connections was examined. According to both studies, tensioned high-strength bolts significantly increased fatigue life of the bolt hole plate. According to the authors, "this was due to the high pressure under the washers of the bolts. This high pressure gives a certain protection of the area around the hole, so that the stress distribution in the net section

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J. S. Crain, G. G. Simmons, A. B. Matamoros, and S. T. Rolfe, 2150 Learned Hall; C. R. Bennett, 2155 Learned Hall; and R. Barrett-Gonzalez, 2124 Learned Hall, University of Kansas, 1530 West 15th Street, Lawrence, KS 66045. Corresponding author: C. R. Bennett, crb@ku.edu.

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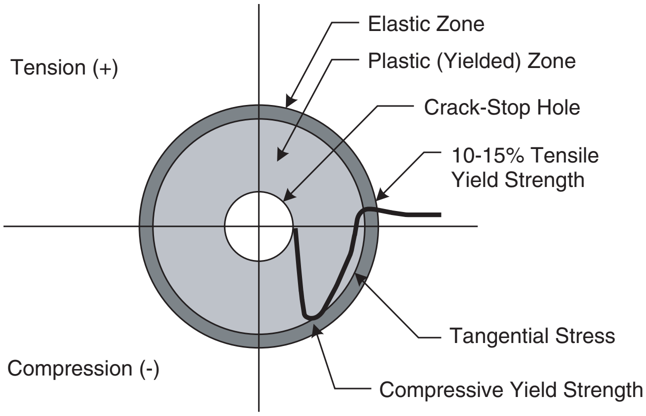


FIGURE 1 Residual tangential (circumferential or hoop) stress surrounding cold-expanded hole.

became much more favorable, even after the slip of the connections" (*17,* p. 306).

The method of installing high-strength bolts does not appear to improve fatigue performance as a result of cold working. No study reported mechanical expansion occurring at the edges of the holes as a result of tensioning the high-strength bolts (*16–18*). Installing tensioned high-strength bolts is a separate technique and is one that potentially could be coupled with cold working to produce even larger improvements in fatigue life.

The technique described in this article used piezoelectric actuators to work dynamically and cold-expand the volume of steel plate surrounding the inner surface of a crack-stop hole. Dynamically working steel through impact at high frequencies is a proven method for refining coarse-grained steel into finer grained material (*19*), which can translate into improved fatigue performance. Plastic strains induced by the cold-expansion from the piezoelectric transducers were intended to create a residual compressive stress field similar to that achieved through existing techniques. The technique discussed in this paper has been termed "piezoelectric impact compressive kinetics" (PICK).

BACKGROUND

Existing Cold Working Techniques

While development of the PICK technique has focused solely on improving the fatigue performance of steel bridges, similar challenges are commonly encountered in the aerospace industry. Fastener holes in aircraft structures are sources of large stress concentrations and, as a result, are potential sites for cracks to initiate and propagate. It is common practice in the aerospace industry to cold-expand fastener holes, often improving fatigue life by 3 to 10 times compared with an untreated hole (*11*). Most of the development of cold expansion has been within the aerospace field. As a result, most existing studies involve numerical modeling and testing with various grades of aluminum, titanium, and high-strength steel (*20*). Benefits obtained from cold expansion of mild-grade steel are expected to be similar to those found in aerospace-industry materials as a result of the similarity in the stress–strain relationship of the two types of materials when stressed beyond yield.

The most common technique currently used to cold-work fastener holes in aerospace applications is the split sleeve mandrel process (Bonnie Kensmoe, personal communication, July 31, 2009). A thorough review of the literature on this topic did not expose any application of this technique to bridges, but it has been used extensively in other structural applications. The process utilizes a solid, tapered mandrel and an internally lubricated steel split sleeve. Application of this technique begins by positioning the sleeve over the mandrel and inserting the mandrel into the hole. The hole is then expanded as the mandrel is drawn back through the sleeve. The expanded sleeve remains in the hole and can be discarded. It is common practice to remove damage by reaming or drilling the inside of the fastener hole (*21*).

Crack-Stop Holes

Current methods used to determine the size of crack-stop holes needed to prevent crack reinitiation are based on linear-elastic fracture-mechanic theory (*22*). Analytic methods involving linear-elastic fracture mechanics are based on the procedure that relates magnitude of the stress field near the tip of a crack (σ_{max}) to nominal applied stress (σ_{nom}), as described by Equation 1:

$$\sigma_{\text{max}} = k_t \sigma_{\text{nom}} \tag{1}$$

Parameters that affect the magnitude of the stress amplification factor k_t are size, shape, and orientation of the crack or crack-like imperfections. The elastic-stress field at the edge of an imperfection, as described in Equation 2, is derived under the assumption that the shape of the imperfection is either elliptical or hyperbolic (see Figure 2) and the nominal applied stress is normal to the plane of the imperfection.

$$\Delta\sigma_{\text{max}} = \frac{2\Delta K_I}{\sqrt{\pi\rho}} \tag{2}$$

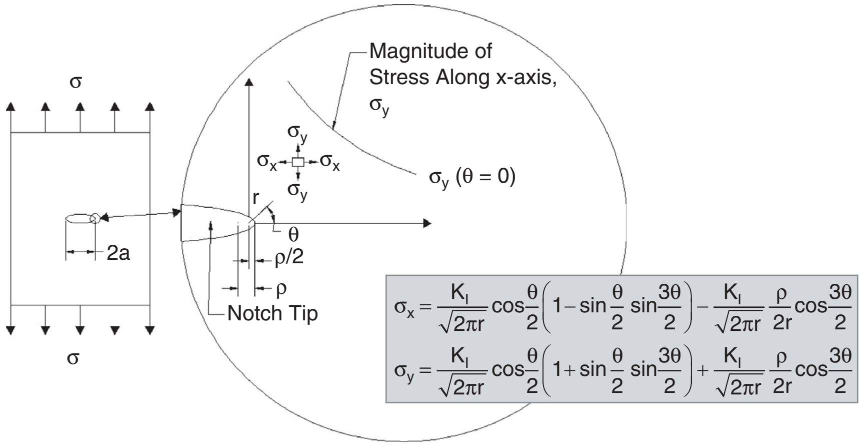
where the stress intensity factor ΔK_I is determined assuming a zero radius crack tip and an initial crack length $a = a_o + \rho$ where ρ is the radius of the hole.

From Equation 2, it is observed that both ΔK_I and the square root of the radius of the notch tip, $\sqrt{\rho}$, affect the magnitude of maximum stress at the edge of the notch. Equation 2, which is valid for relatively sharp notches, is exact only when the notch tip radius is equal to zero. However, finite element analyses have shown that Equation 2 provides a fairly accurate relationship for imperfections with notch tip radii small compared with the crack length, 2*a* (*23*). The theoretical relationship between terms ($\Delta K_I/\sqrt{\rho}$) and maximum stress, $\Delta\sigma_{\text{max}}$, led to further laboratory investigation to study its significance to fatigue crack initiation life. Thus, through basic fracture mechanic theory and extensive laboratory testing, Equation 3 was derived (*22*) and can be used to determine the minimum crack-stop hole radii needed to prevent crack reinitiation in steel bridges:

$$\rho = \left(\frac{\Delta K_{\text{total}}}{10\sqrt{\sigma_{ys}}}\right)^2 \tag{3}$$

where ΔK_{total} is stress intensity factor and σ_{ys} is yield strength under static loading.

An example of how Equation 3 may be used in a practical application is presented as follows. A fatigue crack is found during an inspection in the web of a bridge girder, near the top flange. The crack runs longitudinal to the girder, as shown in Figure 3, and is



$$\sigma_x = \frac{K_I}{\sqrt{2\pi r}}\cos\frac{\theta}{2}\left(1 - \sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right) - \frac{K_I}{\sqrt{2\pi r}}\frac{\rho}{2r}\cos\frac{3\theta}{2}$$

$$\sigma_y = \frac{K_I}{\sqrt{2\pi r}}\cos\frac{\theta}{2}\left(1 + \sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right) + \frac{K_I}{\sqrt{2\pi r}}\frac{\rho}{2r}\cos\frac{3\theta}{2}$$

FIGURE 2 Schematic of elastic-stress field distribution near tip of an elliptical crack.

216 mm (8.50 in.) long, offset 12.7 mm (0.500 in.) from the top flange. Therefore, there is sufficient space for a crack-stop hole with an approximate diameter of 25.4 mm (1.00 in).

For the fatigue crack scenario presented, the steel in the girder web is Grade A36 with a yield strength under static loading $\sigma_{ys} = 248$ MPa (36.0 ksi). For the 216-mm (8.50-in.) crack, the stress intensity factor, ΔK_{total}, can be determined as follows (the following calculations are provided in U.S. standard units as Equation 3 is not dimensionally independent):

$$\Delta K_{\text{total}} = \Delta\sigma\sqrt{\pi a}$$

$$\Delta K_{\text{total}} = \left(26.0^{\text{ksi}}\right)\sqrt{(\pi)\left(\frac{8.50^{\text{in.}}}{2}\right)} = 95.0\ \text{ksi}\sqrt{\text{in.}} \qquad (4)$$

The value of 179 MPa (26.0 ksi) assumed for the nominally applied stress was taken from previous finite element studies (*3, 4*), which quantified the nominal stress demand at web gaps of details similar to that shown in Figure 3. The radius required to prevent further crack propagation can then be directly solved with Equation 3:

$$\rho = \left(\frac{95.0^{\text{ksi}\sqrt{\text{in.}}}}{10\sqrt{36.0^{\text{ksi}}}}\right)^2 = 2.51\ \text{in.}$$

Therefore, the required crack-stop hole diameter for the 216-mm-long crack is about 127 mm. For this crack length, there is not enough space to install a properly sized crack-stop hole; even if there were, the 127-mm diameter appears to be excessive. Given the dimensional constraints, the hole would have to be undersized. The 25.4-mm-diameter hole could serve as a temporary aid to retard the crack from propagating. However, the fatigue crack eventually would reinitiate and propagate away from the edge of the undersized hole until failure of the structural member or additional repair. This situation is often typical for crack-stop hole design scenarios, where the hole diameter needed to prevent crack reinitiation is too large to be implemented.

Objective

The objective of this study was to explore the potential for inducing residual compressive stresses in undersized, drilled crack-stop holes to extend the fatigue life of steel bridges. The residual stresses are induced with a PICK tool. A significant body of work with cold expansion has been developed in the aerospace field over the past three decades, and one goal of this paper was to provide a meaningful link between existing technologies developed for application in the aerospace industry and practical needs within the steel bridge industry.

DEVELOPMENT OF PICK TOOL

A proof-of-concept prototype tool was developed for the laboratory, which used ultrasonic piezoelectric actuators. The PICK tool was used to treat Grade A36 steel fatigue specimens, which consisted of

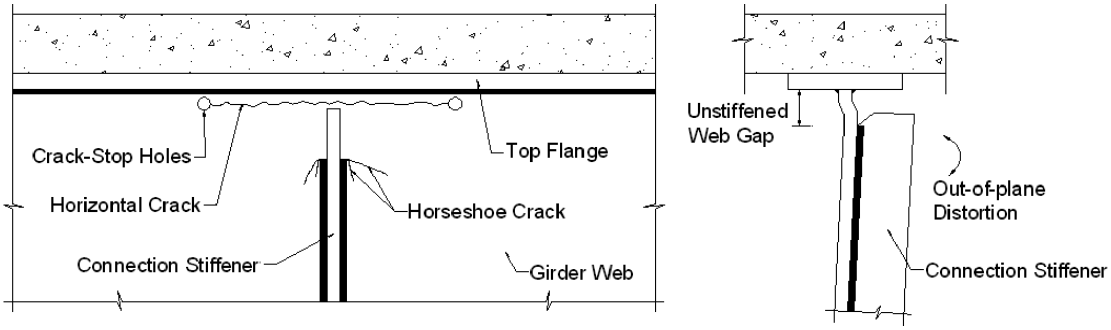


FIGURE 3 Fatigue crack caused with drilled crack-stop holes in steel bridge girder.

a 3.18-mm (0.125-in.)-thick × 760-mm (30.0-in.)-long plate fabricated with various widths. The minimum width of the cross section was 31.7 mm (1.25 in.) at the center of the plate. A 3.18-mm-diameter hole was drilled precisely at the center of the specimen and an aluminum plug was pressed into the hole. The PICK tool utilizes piezoelectric actuators, which deform proportionally to a harmonic electric signal, inducing a harmonic load large enough to plastically deform the aluminum plug inside the hole, causing the hole to expand. After the hole was plastically expanded, the plug was carefully removed from the hole, exploiting the thermal mismatch between steel and aluminum.

The PICK device was powered by a signal generator supplying a sine wave and an amplifier circuit. A strip of piezoelectric material was attached to the rear of the tool to measure the acceleration response of the tool. A strain gauge was attached to the inside surface of the vertical element of the PICK tool to measure the strain induced by tightening the bolt and from the sine wave excitation. A calibration curve was developed to establish a relationship between the load applied to the aluminum plug and the strain measured on the PICK tool, which allowed the load imparted from the transducers during application to be directly evaluated. Figure 4 shows the PICK tool and a steel specimen being treated.

The aluminum plug used as expansion media within the crack-stop hole was 3.18 mm tall × 3.18 mm diameter 6061-T6 aluminum with 276-MPa (40.0-ksi) nominal yield strength. In operation, the plug was pressed into the specimen and the integral bolt was tightened on the PICK device until the load was large enough to cause yielding of the aluminum plug. Because the amount of strain energy in the steel is proportional to the strain, a frequency sweep was performed until the measured strain was maximized, at a frequency corresponding to a natural frequency of the PICK device. Operating the tool at this frequency maximizes the distortional energy applied to the steel specimen being treated. Typically, the frequency ranged between 30 and 34 kHz (outside the audible range) and the strain ranged between about 220 and 320 microstrains. The strain values corresponded to loads of 9.56 kN (2.15) kips and 13.9 kN (3.12 kips) on the aluminum plug.

The effect of the deformation on the inside of the hole was evaluated analytically and compared with results from two- and three-dimensional finite element analyses that examined the performance of uniformly expanded crack-stop holes. The two- and three-dimensional uniform expansion finite element analyses were validated through comparison with similar uniform expansion models performed on aluminum plates, reported in aerospace engineering literature and replicated in this study to serve as a basis for comparison. An ongoing experimental thrust aimed at evaluating the fatigue performance of PICK-treated crack-stop holes is not described here. This article focuses instead on the feasibility of achieving sufficient residual stresses and the characteristics of the necessary expansion to have a beneficial effect on fatigue life of steel bridges.

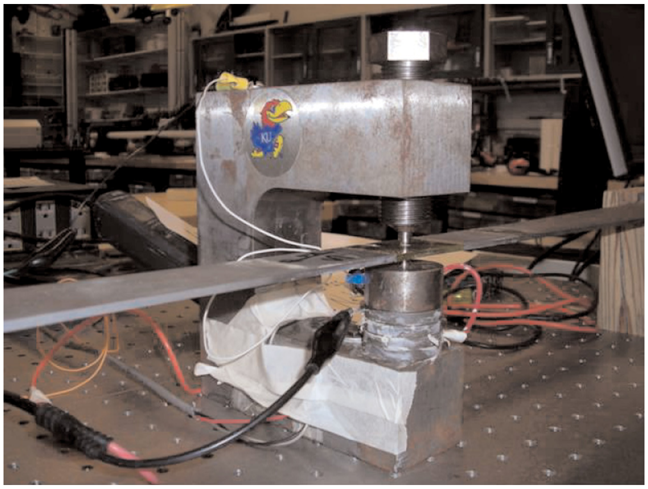


FIGURE 4 PICK tool being used to treat a crack-stop hole in a steel fatigue specimen.

METHODOLOGY

Closed-Form Solutions

Previous analytic investigations of cold expansion (*11, 13, 15, 24, 25*) have been based largely on two-dimensional approximations. These closed-formed solutions have been applied to both the plain-strain condition of the thick-walled cylinder and the plain-stress condition of holes in infinitely wide plates. These analytic simplifications used both Tresca and von Mises yield criteria with assumptions of either elastic-perfectly-plastic or strain-hardening material properties. These closed-form solution techniques have been extensively reviewed (*14*).

Each method reported attempted to quantify and characterize the level of residual stress that could be achieved through cold expansion. Each method of analysis was consistent in showing that a level of residual compressive stress approximately equal to the yield strength of the material could be achieved in the tangential direction near the edge of a hole. These methods have also shown that the residual compressive stresses decay rapidly in the radial direction and ultimately change to tensile stresses at a point referred to as the elastic–plastic boundary, r_p. From these studies, the maximum r_p is shown to occur about one hole diameter away from the hole edge and has been shown to be a function of the different levels of expansion.

Uniform Expansion of Crack-Stop Holes

A significant body of literature exists describing numerical simulation studies that have been done with the intent of comparing uniform levels of expansion with existing cold expansion techniques. Most of these studies simulated the process of split sleeve mandrel cold expansion in aluminum plates, a common application in the aerospace field. For the study described here, a similar analysis approach was used to compare uniform expansion of mild steel with expansion created by the PICK tool technique.

The material properties of the aluminum and mild steel uniform expansion models are shown in Table 1. Values reported for the

TABLE 1 Material Properties Used for Models Simulating Uniform Expansion

Material	Modulus of Elasticity, MPa (ksi)	Yield Strength, MPa (ksi)	Ultimate Strength, MPa (ksi)	Poisson's Ratio
Aluminum	77,220 (11,200)	312 (45.2)	440 (63.8)	0.35
Mild steel	200,000 (29,000)	319 (46.3)	463 (67.2)	0.30

mild steel are from tensile tests performed as part of this study, and the values used for aluminum are from the literature.

ABAQUS, a general-purpose finite element program capable of nonlinear, large-deflection, plastic analysis, was used as the analytic engine. The first task was to create a two-dimensional model in ABAQUS with aluminum material properties, with the purpose of corroborating results with those from published studies. After results from the two-dimensional aluminum model were confirmed, a similar two-dimensional model was created with material properties for mild steel as determined from standard tension tests.

Previous research has shown that an optimum level of cold expansion of a fastener hole using accepted cold expansion techniques is about 4% larger than the original hole size (*9, 25, 26*). The general equation governing the degree of expansion, *i*, is as follows:

$$i = \frac{D_e - D_0}{D_0} \times 100\% \qquad (5)$$

where D_e is equal to the hole diameter after expansion has occurred, and D_0 is hole diameter before expansion. This optimum level of expansion, 4%, is the level at which minimal additional benefit is gained with increased levels of expansion. Two-dimensional mild steel and aluminum models created for this study examined four uniform levels of expansion: 3%, 4%, 5%, and 6%.

The uniform expansion ABAQUS models were created by a two-step process. To obtain the desired level of uniform expansion in each of the four two-dimensional models, an outward displacement was induced and the inside of the hole was expanded to the levels described previously. Then, the uniform displacement was removed, and a permanently deformed surface with residual stresses remained.

After general behavior was confirmed for the two-dimensional models, four three-dimensional models were created to analyze the change in residual stress through the thickness of the specimens under uniform expansion with the same levels of expansion as studied in the two-dimensional models. The three-dimensional models were created to have the same dimensions and thickness of the 3.18-mm-thick mild steel fatigue specimens used in axial fatigue tests. Figure 5*a* shows the mesh geometry in the three-dimensional models as well as the residual stress field around a hole in a mild steel plate after 6% uniform expansion.

Plug–Plate–Tool Interaction Model

A three-dimensional finite element model was created to examine the plug–plate–tool interaction behavior specific to the PICK method of treatment. The model required the large-displacement, nonlinear, plastic-material capabilities of ABAQUS to perform the analysis and included the aluminum plug and a 50.8-mm (2.00-in.) length of the plate. Material properties used were from tension tests of the Grade A36 plate and from published typical curves (*27*). Load was applied as a nonfollowing surface traction to the top and bottom of the plug, and the plate was simply constrained in all directions at discrete locations along the edges. Eight-node, three-dimensional, hybrid continuum elements with incompatible modes were used in all plug and plate parts. The surfaces between the plug and the plate were modeled as frictionless contact surfaces. To achieve convergence of the highly nonlinear analysis, automatic stabilization was included in all steps by specifying a dissipated energy fraction of 0.004.

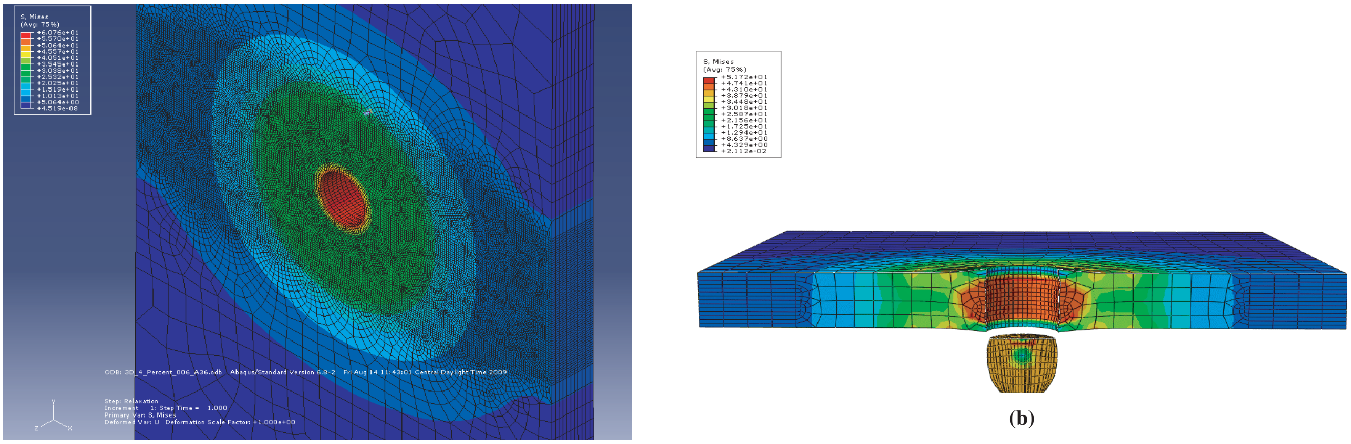
The analysis was performed through a series of steps, first loading the plug on its exposed surfaces so that it expanded inside the plate. The restart feature in ABAQUS allowed the converged configuration to become the new base model for the step to remove the plug. In this step, the plug was removed by specifying a linear displacement of both top and bottom surfaces of the plug. After the plug was removed, residual stresses were examined. Figure 5*b* shows the permanently deformed shapes of the crack-stop hole and plug.

RESULTS AND DISCUSSION

Uniform Expansion of Crack-Stop Holes

The results for the two-dimensional aluminum models were comparable in shape and magnitude to published finite element studies (*9, 28*). The level of tangential residual stress was shown to be approximately equal to the yield strength of the material and the transition from compressive to tensile stresses was shown to occur at approximately the diameter of the hole away from the edge of the hole.

There was a slight difference between the two-dimensional mild steel and aluminum model results in the shape of the residual tangential stress fields, as highlighted in Figure 6. Results for the



(a)

(b)

FIGURE 5 Screenshots from (*a*) three-dimensional modeling of uniform expansion and resulting residual stresses in a crack-stop hole and (*b*) cross-section view of plug–plate–tool interaction model showing residual stresses after plug was loaded and removed.

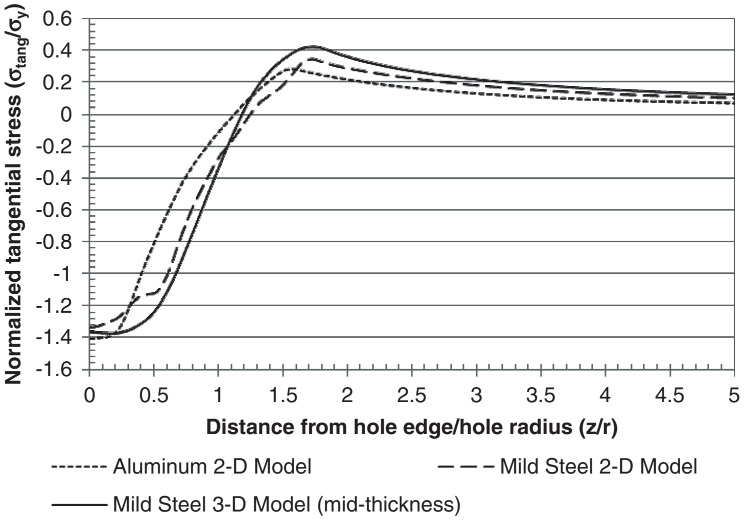


FIGURE 6 Tangential residual stress normalized with respect to material yield strength comparing model results for aluminum and mild steel at 4% uniform expansion.

two-dimensional mild steel model showed a slight discontinuity in the curve after the level of residual stress reached a value approximately equal to the yield strength, which was not observed with the aluminum models. This difference is believed mostly to be a result of the yield plateau implemented in the mild steel model. Tangential residual stresses induced by 3%, 4%, 5%, and 6% expansion in the three-dimensional mild steel model are presented in Figure 7.

The three-dimensional model for a uniform 4% expansion in a 3.18-mm-thick mild steel plate displayed results similar to the two-dimensional mild steel models at mid-thickness of the plate, as indicated in Figure 8. However, the level of tangential residual stress achieved at mid-thickness, –437 MPa (–63.4 ksi), was greater than that found at the edges of the plate, –370 MPa (–53.7 ksi). This finding was consistent with results from previous studies (*9, 28*). The higher level of tangential stress found at mid-thickness was thought to be a result of the constraint provided by the thickness of the plate.

Plug–Plate–Tool Interaction Model

Finite element analyses of the plug–plate–tool model showed that the PICK device deformed the aluminum plug well into the plastic range, causing the plug to develop a barrel shape. As the top and bottom of the plug were compressed, the top and bottom surfaces of the plug deformed inside the corresponding surfaces of the plate, losing contact with the edges of the hole. This process resulted in nonuniform expansion of the inner surface of the crack-stop hole. The analyses also showed that the inside of the hole expanded well into the plastic range, although not uniformly.

Residual tangential stresses on the inside of the hole in the uniform expansion model were found to vary uniformly through the plate thickness; however, the three-dimensional plug–plate–tool model showed that the residual tangential stresses were in tension at the surfaces [90 MPa (13 ksi)] and compressive [–270 to –349 MPa

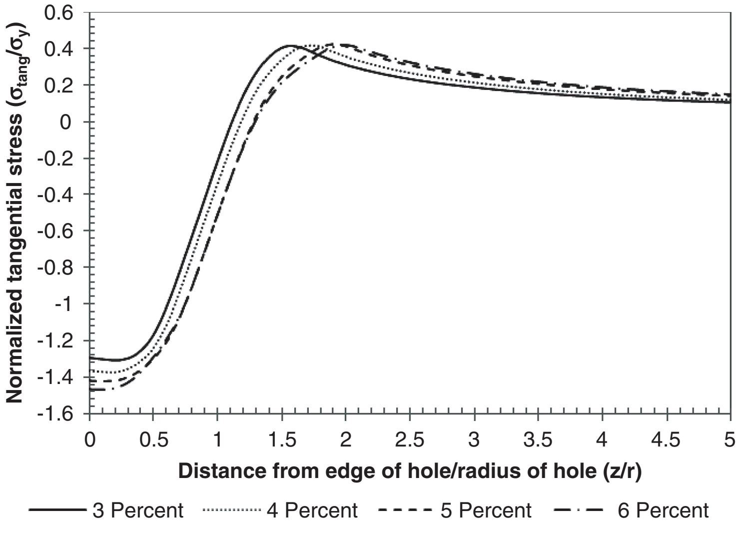


FIGURE 7 Tangential residual compressive stress fields resulting from uniform expansion in mild steel three-dimensional models.

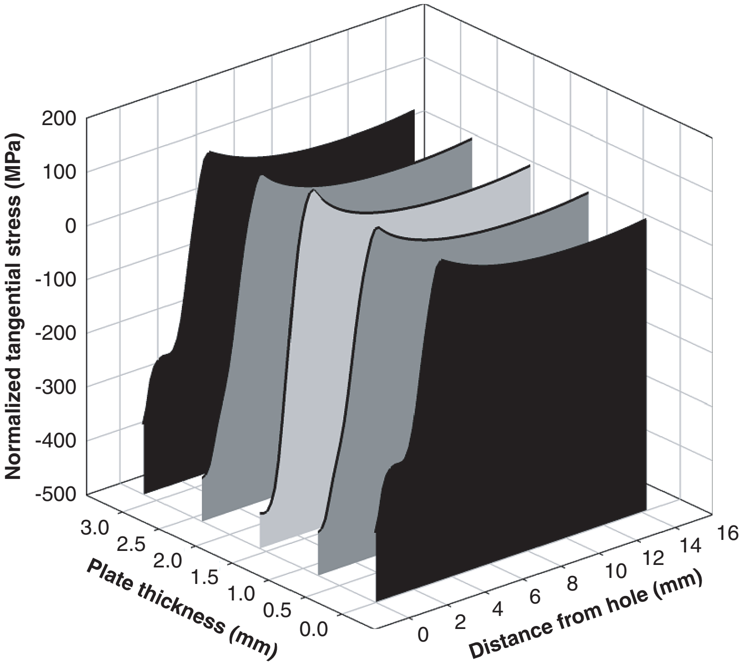


FIGURE 8 Through-thickness residual stress distribution three-dimensional model with uniform 4% expansion.

(−41.0 to −53.0 ksi)] through the center as a result of the deflected shape of the plug, as detailed in Figure 9.

The expansion from the three-dimensional plug–plate–tool model analyses was found to agree with the measured expansion for the treated specimen; in the center of the hole, the model and physical measurements both showed about 7% expansion. The analyses showed that the maximum expansion was similar to that required to obtain maximum benefit for an undersized hole. However, the analyses also highlighted that the expansion at the plate surfaces was less than that at the center. The measured expansion at the plate surfaces was found to be much less than that needed to improve significantly the fatigue performance of an undersized

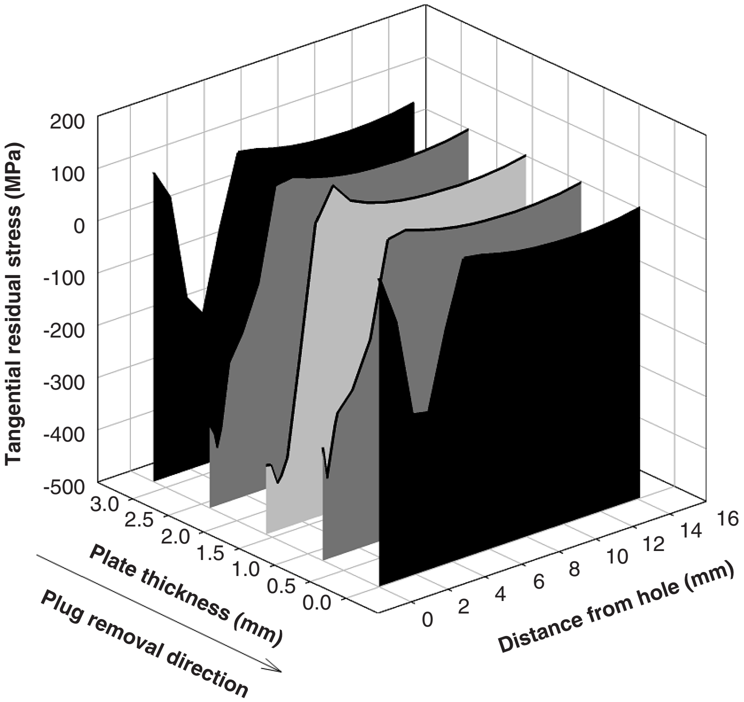


FIGURE 9 Through-thickness residual stress distribution three-dimensional plug–plate–tool interaction model.

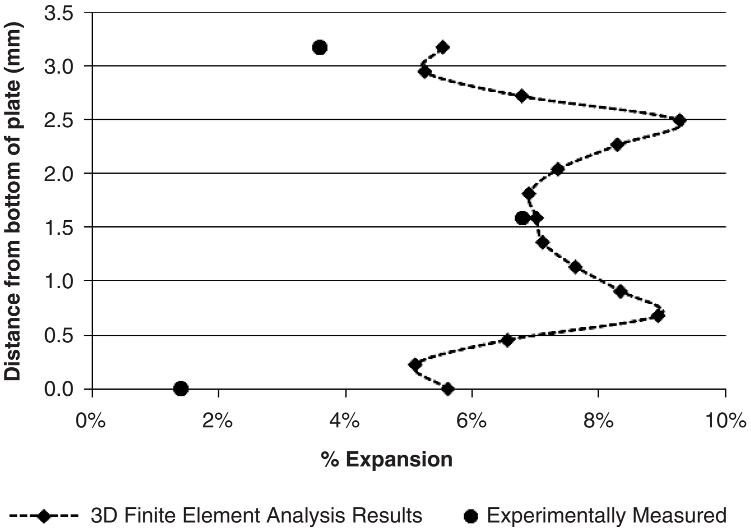


FIGURE 10 Percent expansion from finite element analysis compared with measured expansion at top, bottom, and middepth of treated crack-stop hole.

hole. The difference between the analyses and the measured expansion was likely due to difficulties in perfectly aligning the tool with the plug and indicates that further refinement of the tool geometry is necessary. Figure 10 presents the amount of expansion determined numerically through the thickness of the plug as well as measured expansion amounts at top, mid-thickness, and bottom of a treated crack-stop hole.

CONCLUSIONS

The results of a study exploring the potential of inducing compressive residual stresses in drilled crack-stop holes using an ultrasonic piezoelectric transducer led to the following conclusions:

- A 4% expansion of crack-stop holes in steel plates was found to have an effect similar to that observed in aluminum plates. This conclusion is based on the similarity of normalized tangential residual stress for both materials. This finding is important because it helps to provide a meaningful link between existing research in the aerospace engineering literature and current needs within the field of bridge engineering. Results from the two- and three-dimensional uniform expansion modeling can be interpreted to be independent from the particular technique chosen to cold-expand undersized crack-stop holes and can be used in future studies to corroborate detailed finite element analyses and experimental findings for specific techniques applicable to steel bridges.
- It has previously been shown that the levels of residual stress corresponding to 4% expansion of crack-stop holes in aluminum have been sufficient to improve the fatigue performance of fatigue specimens by an order of magnitude. Because of the general overall similarity in behavior of metals subjected to fatigue loading, it is expected that steel specimens will respond similarly to aluminum when crack-stop holes are treated with 4% or more expansion. Therefore, the results of this study lead to the conclusion that significant gains in fatigue capacity may be realized in mild steel when expansion on the order of 4% or more is achieved in crack-stop holes.
- Finite element analyses and physical measurements of treated specimens showed that the prototype PICK device was capable of expanding an undersized, 3.18-mm-diameter crack-stop hole in a 3.18-mm-thick plate between 5% and 9% at the interior of the hole. These levels of expansion in the steel plates modeled are similar to or greater than levels of expansion noted in identical models on aluminum plates.
- Detailed three-dimensional plug–plate–tool interaction numerical analyses showed that tensile residual stresses were imparted in the treated crack-stop hole at the outer faces of the hole. This finding is important because it represents a need to refine the treatment process so that more uniform compressive residual stresses result from treatment. It is also important because great care was taken in the physical development of this technique to produce uniform compressive stresses in the crack-stop hole; therefore, detailed analyses should be done on all techniques that may be developed in the future to perform a similar task to ensure that undesirable consequences are not being realized.
- Although the crack-stop hole examined was “bench-sized,” results of this study lend confidence to the ability of the device to be scaled up to treat thicker plate material and larger-diameter crack-stop holes and lend credence to the plug–plate interaction treatment approach chosen.

The technique of cold expansion of holes in metallic structures has already been proven as a highly effective retrofitting technique in the aerospace industry. A suite of two- and three-dimensional uniform expansion and detailed three-dimensional plug–plate–tool interaction numerical analyses have shown that a new treatment technique was capable of inducing normalized compressive residual stresses of the same order of magnitude in steel structures as those achievable with current techniques used in aluminum structures. Additionally, two- and three-dimensional uniform expansion models performed as part of this study may be useful to future researchers attempting to achieve compressive residual stresses in steel crack-stop holes with new treatment techniques. Given the success of this technique in the aerospace industry, the potential benefits of using a similar process to improve the fatigue life of existing steel bridges with fatigue cracks are significant.

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