Structural Monitoring and Maintenance, *Vol. 6, No. 4 (2019) 291-315*
DOI: https://doi.org/10.12989/smm.2019.6.4.291

An overview of different retrofitting methods for arresting cracks in steel structures

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(Received June 4, 2019, Revised October 26, 2019, Accepted October 31, 2019)

Abstract. Fatigue cracks are inevitable in circumstances in which the cyclic loading exists. Therefore, many of mechanical components are in a risk of being in exposure to fatigue cracks. On the other hand, renewing the facilities or infrastructures is not always possible. Therefore, retrofitting the structures by means of the available methods, such as crack arrest methods is logical and in some cases inevitable. In this regard, this paper considers three popular crack arrest methods (e.g., drilling stop-hole, steel welded patch, and carbon fiber reinforced (CFRP) patch), which have been compared by using extended finite element method (XFEM). In addition, effects in terms of the width and thickness of patches and the configuration of drilling stop holes have been evaluated. Test results indicated that among the considered methods, CFRP patches were the most effective means for arresting cracks. Besides, in the case of arresting by means of drilling stop holes, drilling two holes next to the crack-tip was more effective than blunting the crack-tip by drilling one hole. In other words, the results indicated that the use of symmetric welded metal patches could lead to a 21% increase in fatigue life, as compared to symmetric stop holes. Symmetric CFRP patches enhanced the fatigue life of cracked specimen up to 77%, as compared to drilling symmetric stop holes. In addition, in all cases, symmetric configurations were far better than asymmetric ones.

Keywords: fatigue crack; CFRP and steel patch; crack arrest; stop-hole; retrofit

1. Introduction

A structural element, during its service life, is exposed to the risk of fatigue cracks, thermal stresses and initial defects. These items could decrease the life cycle of the elements. In such circumstances, the cracks and defects could affect the performance of the structure (Karamloo *et al*. 2016, Karamloo *et al*. 2016, Mazloom and Karamloo 2016, Karamloo *et al.* 2017, Mazloom et al. 2017, Mazloom and Karamloo 2019, Roudak and Karamloo 2019). Therefore, the cracked element should be either repaired or replaced. However, in most cases, the economic or technical conditions of the structure or project necessitate the former option. For instance, for some infrastructures, such as large bridges, in which the replacement of the cracked element is a technical and economic burden, the best method is to retrofit the element by using the existing

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http://www.techno-press.org/?journal=smm&subpage=7 ISSN: 2288-6605 (Print), 2288-6613 (Online)

techniques (Mazloom and Mehrabian 2006, Mazloom 2008, Mazloom 2010, Mazloom 2013, Mazloom *et al.* 2015, Nazary and Mazloom 2016, Mazloom *et al*. 2017, Roudak *et al.* 2017, Gholipour and Mazloom 2018, Karamloo and Mazloom 2018, Mazloom *et al.* 2018, Karamloo *et al.* 2019, Mazloom and Miri 2017, Mazloom *et al*. 2018, Afzali Naniz and Mazloom 2018). Fatigue loading is one of the most prevalent load conditions in infrastructure elements. Hence, understanding the methods of fatigue crack arrest is necessary. There are various methods for crack growth retardation (Domazet 1996), such as crack filling (Wolf 1970, Sharp *et al*. 1997, Shin and Cai 2000), application of welded metal patches (Domazet 1996), CFRP patches (Emdad and Al-Mahaidi 2015, Aljabar *et al.* 2016, Colombi and Fava 2016, Hu *et al*. 2016, Aljabar *et al*. 2017, Hosseini e*t al.* 2017, Wang *et al.* 2017), welding, application of residual compressive stresses (Ayatollahi *et al*. 2015), and drilling stop holes (Ayatollahi *et al.* 2015, Ayatollahi *et al*. 2016, Razavi *et al.* 2017).

Among the existing crack arrest methods, drilling stop holes, welding or riveting a metal patch, and installing a CFRP patch are of the most common and efficient methods. In this regard, the state of art has been reviewed carefully. In addition, these three mentioned method of retrofitting of a cracked steel plate have been investigated and compared numerically by using the extended finite element method. To do so, a steel plate with a central crack has been considered as a flawed element, to be retrofitted by those mentioned methods. Two different cases of drilling stop holes, four cases of welded metal patches, and four cases of CFRP patches have been investigated and compared under a circumstance in which a low cycle fatigue regime of loading was applied to the specimen.

2. State of art review

2.1 Stop-hole technique

During a service life of a structural member, cracks are very often generated due to many reasons (Ayatollahi *et al.* 2015). Hence, a method, whose aim is to extend the life of the member, is needed to avoid catastrophic failures. Drilling stop holes close to the tip of the crack is one of the most common and accessible methods of retrofitting a cracked steel plate. In general, this technique can be divided into three main categories (Ayatollahi *et al*. 2015): crack flank stop holes, deflecting stop holes, and crack tip stop holes. The crack-tip stop-holes are being used to reduce the stress singularity of the crack tip (Ayatollahi *et al.* 2015). The so-called deflecting stop-holes are being used in order to change the direction of crack path and to retard the propagation rate of the crack. Drilling symmetric flank holes are the other efficient method, which could lead to a reduction of stress intensity factor, a decrease of crack growth rate, and an increase of the lifecycle of the member (Ayatollahi *et al*. 2014). Many researches have been conducted regarding the efficiency of stop-hole technique on fatigue crack growth retardation. For instance, Fu and his co-workers used compact tension specimen to consider the efficiency of this method on steel bridge decks (Fu *et al*. 2017). To do so, they compared the stress concentration and stress gradient before and after the drilling. Besides, they focused on the optimization of the location of the stop holes. The results indicated that the optimum position of the center of the stop-hole is located behind the crack tip and the hole edge coincides with the crack tip. In addition, these researchers suggested hole diameters larger than 8 mm or those weakening the section by 10%. Fu and his co-workers also investigated multi-hole crack stopping (Fig. 1). They recommended the horizontal osition of the flank-hole to be at distance of 25% of a single diameter front, and in front of the single hole. However, in general, a flank-hole was not recommended to be used by them. Besides, they reported that the stop-hole technique could only stop the growing process but not the rate of the crack growth.

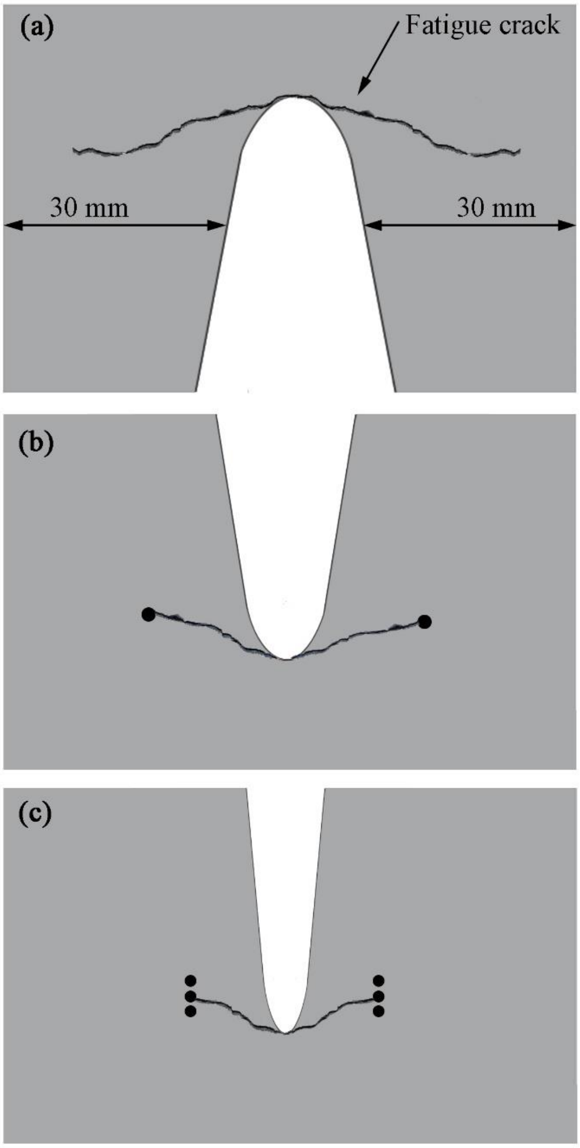

Fig. 1 Drilling methods, investigated in (Fu *et al.* 2017): (a) Original crack, (b) Single hole and (c) Additional holes

A numerical study has been conducted by Ayatollahi and his co-workers on the effect of symmetric flank holes on fatigue life of a single edge notched tension (SENT) specimen made of 2024-T3 aluminum alloy (Ayatollahi *et al*. 2014). They theoretically studied the crack growth retardation, theoretically, by means of drilling two symmetric holes at appropriate location along the crack flanks. Both the effects of arrangements and diameters of the holes on the crack growth retardation were considered. Based on this numerical study, drilling the crack flank holes could lead to a significant decrease in the stress concentration around the tip of the crack along with a decrease in stress intensity factor. They further reported that the best location for these crack flank holes is where the line connecting two holes passes the crack tip. In addition, they reported that the location of the holes could affect the retardation ability of this method of crack arrest. In other words, as the distance between the flank holes and the crack tip decreases the rate of crack growth decreases. In the study, it is reported that reducing the vertical distance between the edges of crack flank holes and the crack line, increases the fatigue life of the specimens. Nateche *et al.* (2016) introduced the concept of drilling repair index in order to evaluate the efficiency of the stop-hole technique. They considered three cases consisted of: A. drilling a single hole at a blunt crack tip; B. drilling a single hole at a distance equal to r from the crack tip with an angle of orientation relative to the crack path equal to θ; C. drilling a second hole, which is located symmetrically to the first near to the crack hole (Fig. 2)

In the other study conducted in 2015, the shape of stop-hole was reconsidered by means of structural optimization techniques (Fanni *et al*. 2015). In other words, they investigated the retardation efficiency of the non-circular holes. The optimized shape was found to yield a fatigue life from 2 to 9 times the life obtained by the circular holes. However, in the opinion of the authors, the method introduced by Fanni and his co-workers is very hard to be practically implemented. Razavi and his co-workers introduced a modified shape for stop holes (Razavi *et al.* 2017), shown in Fig. 3.

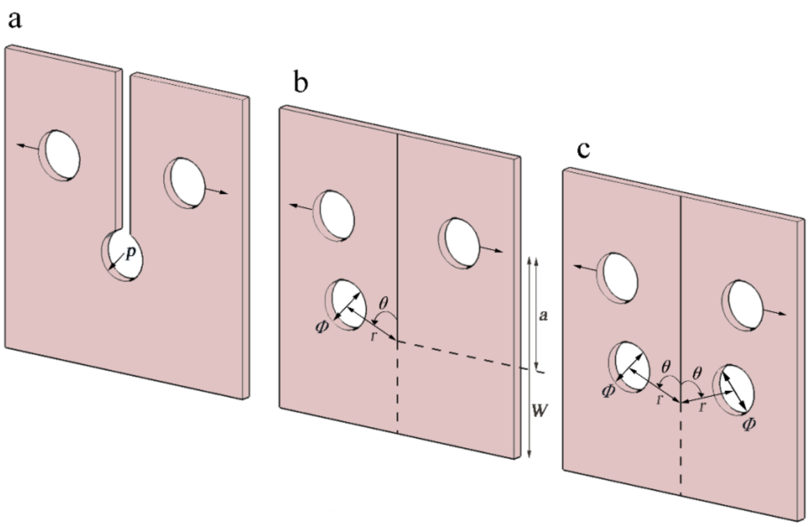

Fig. 2 Configurations studied by (Nateche *et al.* 2016): (a) Ordinary stop-hole, (b) Stop-hole drilled at distance r and with orientation θ with respect to the crack line and (c) Drilling symmetric flank holes

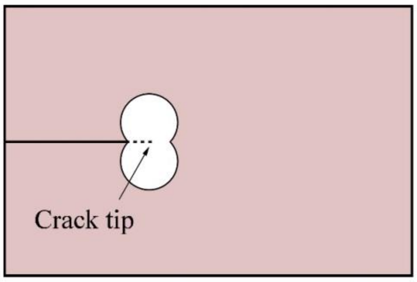

Fig. 3 Shape of the stop-hole introduced by (Razavi *et al*. 2017)

They tested this method on high strength steel S690. They reported that the experiments on fatigue crack initiation/growth along with macroscopic examinations and numerical studies show that this method significantly increases the efficiency of retardation. They further reported that the stress condition around the stop hole was considerably affected by the size and the arrangement of the stop holes. It should be noted that this idea was first investigated on a theoretical basis by Ayatollahi and his co-workers (Ayatollahi *et al*. 2016).

Makabe and his co-workers (Makabe *et al.* 2009) conducted an interesting study regarding the stop hole technique. A series of fatigue crack growth tests have been conducted by them. In some cases of crack growth tests, holes have been drilled near the cracks, while in other specimens, pins have been inserted in the drilled holes. The results of the study showed that the addition of the pins improved the crack arrest ability of the stop hole technique. They further discussed that although inserting pins lead to an increase of compressive residual stress, it was efficient for crack growth retardation. Pedetsen (2004) considered the stop hole technique from an optimization point of view and answered two main raised questions, i.e., 'where is the best place of the hole?', and 'what is the best shape of the hole?'. For the former, he extended the findings regarding the isotropic materials, to include the behavior of orthotropic materials. However, for the latter, he considered non-circular shapes and claimed that these kind of shapes can significantly improve the stress field at the crack boundary. Moreover, he analyzed and optimized the effect of stress shielding for orthotropic materials by drilling circular holes away from the crack tip. Based on petersen's study, the optimum place for the crack flank holes is where they situated, close to but behind, the crack tip. In addition, he reported that the position of the crack flank holes was neither related to orthotropy of the cracked length nor to the height over the crack. However, these two items could naturally affect the stress intensity factor. To the authors' best knowledge, studies comparing different methods of crack arrest are lacking. One of the main studies in this context was conducted by Shin *et al*. (1996). They considered different methods of crack arrest including drilling crack flank holes, infiltrating epoxy resin, alumina powder and a mixture of both as well as evaluating the effect regarding the introduction of overload. In the mentioned study, it is reported that the best retardation effect was achieved by drilling closer to the crack plane.

2.2 Retrofitting by composite patches

2.2.1 Retrofitting steel plates by non-pre-stressed composite patches

The use of composite patches for crack arrest was mainly started by Baker and Jones (Baker and Jones 1988) in Australia. After the consideration of the efficiency of this method, more attention has been paid to this subject. One of the common problems, which structural engineers are facing, is the fatigue sensitive details in aging steel girders (Tavakkolizadeh and Saadatmanesh 2003). In this regard, Tavakkolizadeh and Saadatmanesh studied the effect of CFRP patches on fatigue strength of steel girders (Tavakkolizadeh and Saadatmanesh 2003). To do so, they tested 21 notched beam specimens made of $S127\times4.5$ A36 steel retrofitted with CFRP patches under medium cycle fatigue loading condition. The specimens were tested under 4-point bending configuration with the loading rate of between 5 to 10 Hz. They also considered different constant stress ranges between 69 and 379 MPa. The results of the mentioned study showed that the patches of CFRP not only decrease the rate of crack growth but also they extend the life of specimens up to three times. Actually, the specimens under stress ranges of 345 and 207 MPa showed longer fatigue lives of 2.6 and 3.4 times than the unretrofitted specimens, respectively. In addition, based on the mentioned study, the use of CFRP patches have affected the stress reduction process. In other words, the retrofitted specimens have confronted the decrease of stiffness at crack lengths about 22.5 mm, while, the unretrofitted ones showed a stiffness decrease for crack lengths about 14.5 mm. In a study conducted by Khalili and his co-workers (Khalili *et al*. 2005), the retardation performance of glass fiber reinforced composites (GFRP) and fiber reinforced metal laminates (FML) has been assessed under different loading conditions. It is reported that FMLs have better performance in tensile, three-point bending, and impact loading tests than the GFRP. In a study conducted by Lam et al. (Lam *et al.* 2010), the behavior of single-side carbon fiber-reinforced polymer patching has been considered. To do so, the strain distribution in the vicinity of the cracked region has been measured. The results showed that the crack tip strains significantly decreased when the patch was installed. They also proposed a model called modified three-layer model, which is claimed to be a good mean for prediction of strain distribution. Their finite element model, which was based on the so-called modified-three-layers model, indicated that the SIF at the tip of the crack, through the thickness of the plate, varies through the thickness of the cracked steel plate with single-side patching. Based on the mentioned model, it is claimed that the width and length of patches have only a negligible influence on the SIF, albeit the influences regarding the number of layers of the patching were so pronounced (Lam *et al*. 2010). It is worth noting that the main drawbacks of the so-called three layers model are overestimation of SIF on the patched side as well as the underestimation of SIF on the unpatched side of the plate (Lam *et al*. 2010). Roberts investigated the fatigue and bond behavior of thick steel plate retrofitted by CFRP (Roberts 1995). The retrofitting performance of CFRP plates on riveted steel bridges was studied by (Bassetti *et al.* 2000, Colombi *et al*. 2003). They used finite element analysis to study the effect of CFRP on stress intensity factor of the plate. Their results showed that the SIF was notably decreased by means of bonded patch. They also further studied the effect of inducing compressive stress to the adherend on crack closure effect (Bassetti *et al.* 2000, Colombi *et al.* 2003). In another study, by considering two different configurations for crack (center crack and symmetric edge notched crack) and two different types of CFRP (the so-called CFRP plate and CFRP sheet) the retrofitting performance of this material for the extension of steel fatigue life has been assessed (Jones and Civjan 2003). They reported that the maximum increase in fatigue life was about two times. Liu and his co-workers tested fifteen CFRP/steel double lap joints with different types of

CFRP composites (normal and high modulus) and different bond lengths under fatigue loading with different ratios (Liu *et al.* 2005). They reported that in circumstances that the maximum load is less than 35% of the ultimate static strength, the influence of fatigue loading on the bond strength is not notable. Another issue in civil engineering is serviceability and fatigue strength of the old metallic structures. A notable work has been conducted by (Täljsten *et al.* 2009). They reported that the use of non-pre-stressed CFRP patches could lead to an enhancement of fatigue strength for about 2.45-3.74 times. Hansen *et al.* conducted fatigue tests of eccentrically loaded single edge crack tension specimens retrofitted by CFRP patches (Hansen *et al*. 2009). They reported that the load ratio, the adhesive bond, and the crack length are the most significant parameters whose effects are so prominent. The blast response of cracked steel box, retrofitted by CFRP patch, has been scrutinized by (Pereira *et al.* 2011). They modelled the steel material by using isotropic hardening model, pertaining to Von-Mises yielding with isotropic strain hardening. They found out that the use of CFRP patches for retrofitting the steel boxes reduce the stress field around the crack and hence prevent the crack from growing and extend the service life of the steel structure. Besides, this could lead to an enhancement in blast resistance of steel structures. The application of CFRP patches on thin-walled notch-embedded steel cylinders subjected to compression was investigated by (Kabir and Nazari 2011). They tested specimens with unique diameter-to-thickness ratio as well as numerically analyzing the results to reach better understanding about the retrofitting performance of CFRP patches and effect of notches. In another same research, FRP-jacketing technique was used for retrofitting steel tubes and cylindrical shells under compression loading (Teng and Hu 2007). They reported that the use of this jacket enhanced the ultimate strength and deformation for the corresponding member. The nonlinear behavior and load carrying capacity of the CFRP-strengthened cold-formed steel channels was investigated under compressive loading condition (Silvestre *et al.* 2008). Silvestre and his co-workers used externally patched composite, pultruded sheets and reported the optimum location for the patch (Silvestre *et al*. 2008). An experimental and numerical study has been conducted on progressive damage analysis of patched CFRP laminates by (Kashfuddoja and Ramji 2014). They used three-dimensional finite element-based progressive damage model to predict the failure and post-failure of repaired notched panel under tensile loading. In the mentioned investigation, the panels made of carbon/epoxy composite laminates of pure unidirectional and quasi-isotropic stacking sequence were considered. They considered both the single side and double sides circular patching of the same parent material as well as considering both pure unidirectional and quasi-isotropic panels. In the mentioned study, it is reported that the damage in the repaired panel is influenced by localized patch debonding. However, the damage in notched panel always commences along with matrix cracking around the hole (Kashfuddoja and Ramji 2014). Another work, whose goal was design of optimum patch shape and size for bonded repair on damaged CFRP panels, has been conducted by these researchers (Kashfuddoja and Ramji 2014). They used 3D finite element method and investigated the repair efficiency of double-sided patches whose shapes were circle, rectangle, square, ellipse, octagon, and oval. Application of CFRP patches on retrofitting ships could be found in (Karr *et al.* 2016).

2.2.2 Retrofitting steel plates by pre-stressed composite patches

Pre-stressing the bonded composite patches is another promising method to reinforce the cracked detail or to prevent fatigue cracking. One of the most pioneering works in this field goes back to 2003, when Colombi and his co-workers studied the crack growth induced delamination on steel members, which was reinforced by composite patches (Colombi *et al.* 2003). Actually, this method benefits the stresses which induce a crack closure effect. Moreover, by modifying the crack geometry, it reduces the stress intensity range at the crack tip. To evaluate the proposed concept to be used in riveted steel bridges, Colombi *et al.* conducted fatigue tests on notched steel plates reinforced by CFRP patches (Colombi *et al*. 2003). They used an optical technique to observe the crack induced debonded region in the adhesive-plate interface and reported that the efficiency of the crack repair is significantly affected by the size of the debonded region. They further conducted a parametric study to investigate the influences regarding some design parameters such as the Young's modulus of the composite patch, the thickness of the adhesive and the pretension level, on the adhesive-plate interface debond. Colombi (2005) studied the plasticity induced fatigue crack growth retardation model for steel elements retrofitted by pre-stressed CFRP. He tested notched steel plates, reinforced by CFRP patches, and observed that the pre-tension induces compressive strength in the steel plate, which by reducing the stress ratio, it enhances crack growth retardation. By assuming that the rate of fatigue crack growth is a function of strain energy density factor range and through the investigation of the fatigue crack growth data, he concluded that standard crack growth retardation model could not be used to evaluate the minimum effective stress. Therefore, an ad hoc plasticity model was introduced and was verified by the results of experiments. In the model introduced by (Colombi 2005), which is an extension of the well-known Newman's model, the bridging effect of the CFRP strips is analytically modelled. This facilitates the estimation of the reduction of the crack opening displacement, and thus lead to the magnification of the crack growth retardation. Emdad and Al-Mahaidi investigated the fatigue performance of steel plates repaired with CFRP patches (Emdad and Al-Mahaidi 2015). Their tests included unrepaired steel plates, CFRP retrofitted steel plate with center crack, and pre-stressed CFRP retrofitted steel plates with center crack. They reported that pre-stressing the CFRP patches before installation has a predominant influence on fatigue lives of specimens. Besides, it was reported that one single layer normal modulus CFRP sheet could enhance the fatigue life of the specimen up to three times (Emdad and Al-Mahaidi 2015). Moreover, the addition of one layer of CFRP to the mentioned retrofitted system could enhance the fatigue performance of the system up to 30%.

2.2.3 Retrofitting plates of aluminum alloy by composite patches

Aluminum alloys are very commonly used materials in industry. Therefore, a notable attention has been paid to study the methods of crack arrest in this material. Among the arrest methods, the use of composite patches was of the great interest. Baker studied the retrofit efficiency of Boron/Epoxy patches in fatigue crack retardation of aluminum components (Baker 1993). In other words, he considered the effects of boron/epoxy patches, bonded with either an epoxy-nitrite film or an acrylic adhesive, on fatigue crack growth in 2024-T3 aluminum alloy panels. He also proposed a simple model to estimate the reduction of patching efficiency due to cyclic debonding of the reinforcement. Baker, unexpectedly, found that the epoxy-nitrite adhesive was unaffected by temperatures up to $100^{\circ}C$. However, the epoxy/nitrite adhesive showed much lower retardation than patches bonded with acrylic adhesive. Rhee *et al*. considered the fatigue behavior of plasma treated aluminum, patched by CFRP (Rhee *et al.* 2004). In the mentioned study, they also considered the effect of plasma treatment on fatigue properties of aluminum/CFRP specimens by means of testing two different single edge notched specimens of cracked aluminum or plasma treated aluminum both repaired by CFRP patches. In another study, conducted by (Khalili *et al*. 2009), the response of cracked aluminum plates, retrofitted by one-sided composite (CFRP or GFRP) patches, to the Charpy impact was investigated. They used two different materials for composite patches, i.e., in one of them, the woven glass-fibers were used for reinforcement while in the other woven carbon fibers were used for it. In addition, in the study of (Khalili *et al*. 2009) for each case, two lay-ups (i.e., 3-ply and 5-ply) and three different specimen lengths were tested. Based on their experimental results, which they reported, for a given crack length, the 5-ply patch made by woven carbon fibers performed far better than the other cases. Besides, they claimed that the carbon patches perform better than glass patches under impact loading condition. However, they reported that the number of layers has a small effect on fatigue performance of retrofitted specimen. The mentioned study benefited using the so-called "stress ratio= $\frac{E_{patch}t_{patch}}{E_{sheet}t_{sheet}}$ ", in which E and t denote elastic modulus and thickness, respectively. Khalili and his co-workers declared that this ratio has a great contribution to a quantitative evaluation of the efficiency of energy absorption in composite patches (Khalili *et al.* 2009). In other words, they claimed that the patches with small stress ratio are not effective in reinforcing the cracked plates under in-plane impact loading. Actually, the concept of the so-called stress ratio goes back to the study of Ratwani (1978). In the study of the effect of thickness of plates on crack growth rate, he experimentally showed that there is a large difference between the behavior of thick and thin plates. He further reported that the stress ratio plays an important role in fatigue response of retrofitted plates. Therefore, this ratio should be chosen tenderly because a thicker or stiffer patch could lead to a shift in neutral axis and consequently, an unsymmetrical bending (Ratwani 1978). As a matter of fact, the design purposes lead to an attraction of attentions of researchers to the concept of stress ratio. In this regard, based on finite element analysis of composite repair patches, Nagaswami *et al.* (Nagaswamy *et al.* 1995) recommended a stress ratio between 1 and 1.6. In studies conducted by (Schubbe and Mall 1999, Schubbe and Mall 1999) the effects of the patch geometry and stiffness ratio on fatigue behavior of thick and thin cracked aluminum plates were considered. By repairing the cracked plated with one-sided patches, they reported that the optimum stress ratio for thick plates (3.15-6.35 mm) is close to one; while for thin plates, 1.4 is recommended. The stress field of the crack tip of the cracked aluminum plates, repaired with octagonal boron-epoxy patches, were studied by (Okafor *et al.* 2005) through uniaxial tensile loading tests. They reported that the maximum skin stress decreased as the patch was installed and this shifted the maximum stress location from the crack front to the edge of the patch. The performance of the single-sided fiber reinforced composite patches in arresting the cracks in aluminum sheets has been experimentally investigated by researchers such as Sabelkin et al. and Rao and his co-workers (Rao *et al.* 1999, Sabelkin *et al*. 2006). These researchers reported that in some cases, applying the patches could enhance the fatigue behavior of aluminum plates by an order of magnitude (Khalili *et al*. 2009).

Some researchers, such as Pastor and her co-workers, paid attention to the shear strength of the adhesive used to bond composite patch to aluminum plate (Pastor *et al.* 2008). They experimentally observed that the shear strength of an adhesive has a quite important role on fatigue behavior of retrofitted aluminum plate. The fatigue crack growth behavior of 6 mm Al6061-T6 panels retrofitted by single-sided fiber reinforced composite patch was investigated experimentally by (Chung and Yang 2003). They studied the effect of patch length and demonstrated that the behavior of retrofitted plate is influenced by the size of the patch. Ouinas and his co-workers numerically assessed the performance of boron/epoxy and graphite/epoxy patches in fatigue crack growth retardation of aluminum plates with semicircular notch edge (Ouinas, Bouiadjra et al. 2007). They further investigated the effects of patch geometry and the effects of the properties of adhesive on stress intensity factor at crack tip. The double and single patching methodology are also compared with each other and their results revealed that the stress intensity factor of the crack tip with two repair patch is half of the case with one-sided patch (Ouinas, Bouiadjra et al. 2007). By using a finite element based progressive failure model, Papanikos *et al.* (2007) studied the effect of patch geometry on patch debonding initiation and progression of aluminum sheet repaired by CFRP patch. Based on the mentioned study, the stress intensity factor could be influenced by patch width, patch thickness, and adhesive thickness (Papanikos *et al.* 2007). Fig. 4 shows the variation of stress intensity factors because of geometric details of patches.

Another method has been proposed by (Fekirini *et al.* 2008) in which the adhesive layer is divided into two bands with different properties. The first band was attributed to ensure that the stress transfer occurs properly, while the second is adjusted to control the failure of adhesive. It should be mentioned that Fekirini *et al.* studied their method on aluminum plates, repaired with boron-epoxy patches. Using the finite element method, they computed stress intensity factor at the crack tip and found out that the difference of properties between the two adhesive bonds decreased the stress intensity factor. Xiong and Shenoi conducted an experimental survey in which the static and fatigue performance of patches made of three different fiber/epoxy prepregs were assessed for retrofitting a LY12 aluminum alloy (Xiong and Shenoi 2008).

They showed that the kind of material used in patch and its thickness have major contribution in the efficiency of retrofitting. Xiong and Shenoi attributed their observations to the reduction of stress concentration and improvement in the residual strength of the repaired specimens (Xiong and Shenoi 2008). In 1999, Klug and his co-workers compared the fracture behavior of cracked aluminum plates repaired by single and double side patching (Klug *et al.* 1999). In the mentioned paper, the plates were retrofitted by bonding graphite/epoxy on either single side or double sides of the plate. Their results indicated that the double-sided patching could enhance the fracture behavior of the cracked aluminum plate by about 11 times the specimen without retrofitting. This enhancement was reported to be 4.7 times for the single-side patching. A crack arrest study has been conducted to assess the efficiency of CFRP patches on retrofitting a one millimeter- thick 6061-T6 aluminum alloy single-edge-notched tension specimen (Shinde *et al.* 2015).

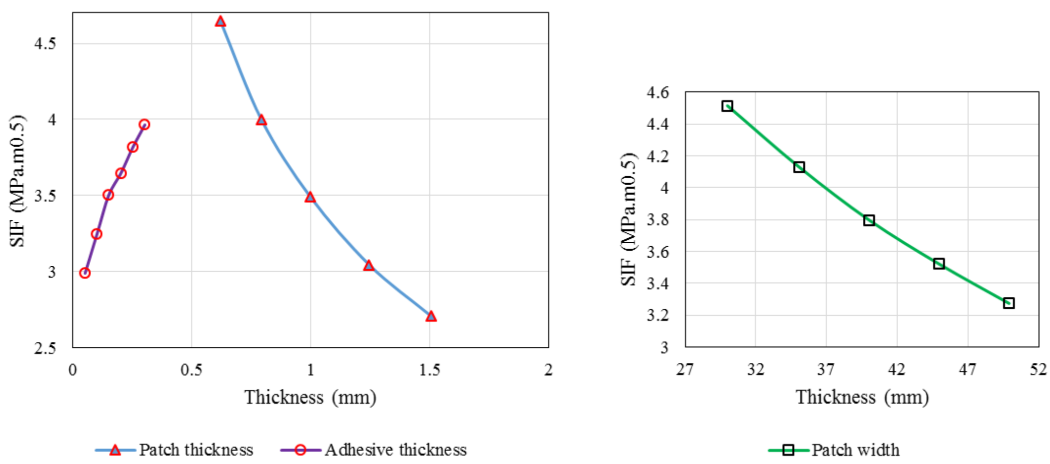

Fig. 4 Effects of repair geometric details on stress intensity factor (Papanikos *et al*. 2007)

They used symmetrical CFRP patches made of several plies and reported that J-integral was reduced drastically. However, the specimen failed at one of the leading edges through separation at the surface (Shinde *et al*. 2015, Shinde *et al.* 2015, Kumar *et al*. 2018, Shinde *et al.* 2018). They further claimed that this separation could be suppressed by tapering all the four leading edges of the patches. They observed that the stress could be doubled in the presence of patches. Retrofitting performance of CFRP patch on fatigue crack growth retardation of AL2014-T6 with inclined center crack has been evaluated using finite element analysis and digital image correlation technique (Srilakshmi *et al.* 2015). They considered both the single and double-sided patching and modeled the adhesive layer by cohesive law. Actually, they determined the properties of adhesive-interface properties by baseline tests. They reported that the resistance of double-sided patch is twice the single-sided patch.

3. Materials and method

3.1 Numerical technique and assumptions

Extended finite element method, mostly known as XFEM, is a robust numerical method through which the physical and mathematical problems with weak or strong discontinuity could be solved. This method enables the scientists to model arbitrary geometric features without showing concern for mesh conformation (Daux *et al.* 2000). The use of XFEM in problems containing crack was commenced by (Belytschko and Black 1999, Moës *et al.* 1999, Stolarska *et al.* 2001). To be more specific, the first idea was to present a method through which the crack propagation could be simulated by using an enriched finite element method technique (Belytschko and Black 1999). This idea includes three major problem; the description of crack, the discretized formulation, and a criterion for updating the crack (Khoei 2015). Moes and his co-workers (Moës *et al*. 1999) used the generalized Heaviside function to model the crack faces away from the crack tip. The junction function concept is then introduced to include the effect of crack branching (Daux *et al*. 2000). They also enriched their method so that it could handle complex problems with voids and multiple holes. A method called level set method (LSM) has been introduced by (Stolarska *et al.* 2001) to model the fatigue crack growth by XFEM. They used this mathematical method to model the moving crack tip at each iteration. In problems with crack, since the variation of stress field near the crack tip is notable, the use of traditional FEM necessitates mesh conforming. Moreover, the existence of crack tip infers asymptotic stress field, which in traditional FEM should be handled manually and iteration by iteration. In addition, the nature of fatigue problems infers moving boundary solution, which is time consuming in traditional techniques of FEM. Hence, in the present study, XFEM coupled with LSM technique has been used to numerically investigate and compare the fatigue retardation of the three main retrofitting method, i.e., drilling stop-hole technique, retrofitting by steel patches, and retrofitting by fiber reinforced composite patches. The parent material was selected to be mild steel with young modulus (E=210 GPa), Poisson's ratio ($\nu = 0.3$). The geometry of the parent material is depicted in Fig. 5. The assumed cyclic loading, whose maximum stress was 70 MPa and the stress ratio ($R = \frac{\sigma_{\min}}{\sigma_{\max}} = 0.1$), is shown in Fig. 6. In addition, the adhesive layer between the composite patch and the parent material was assumed ideal. Figs. 7 and 8 reflect the geometry of the asymmetric and symmetric patches, respectively.

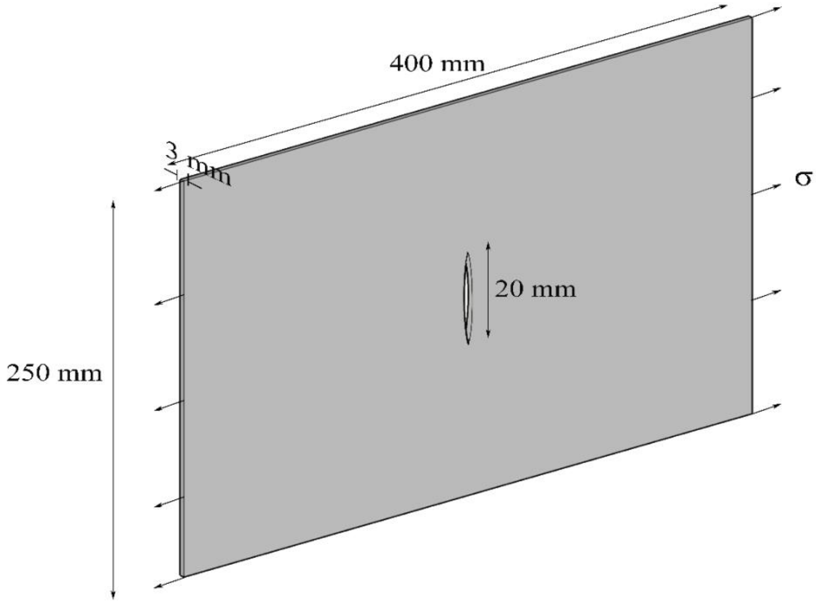

Fig. 5 Geometry of the model (ASTM E647-15e1)

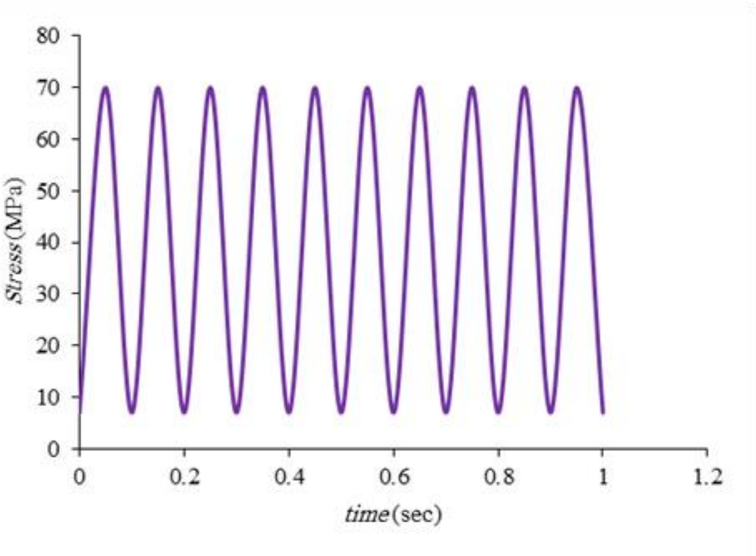

Fig. 6 Loading regime

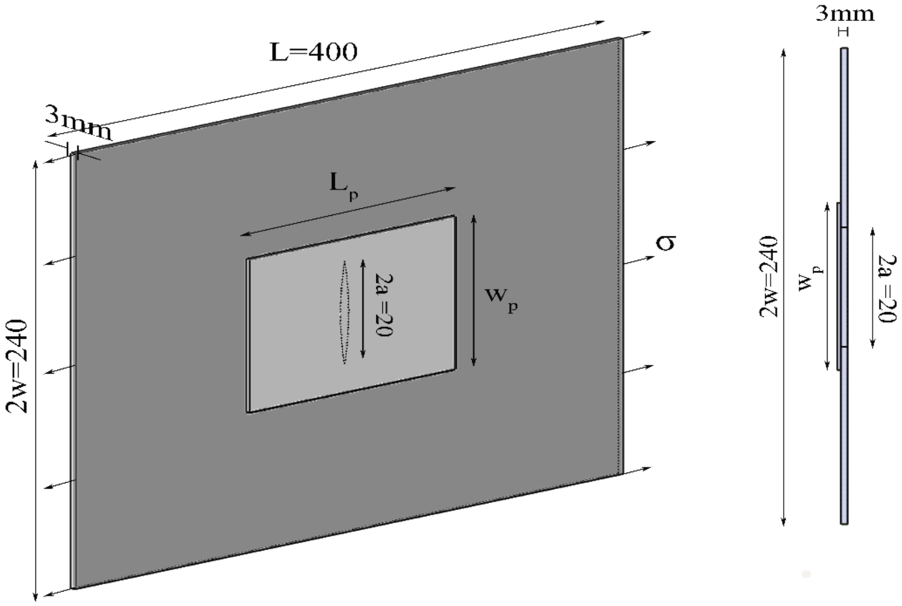

Fig. 7 Geometric properties of one-sided patch (asymmetric)

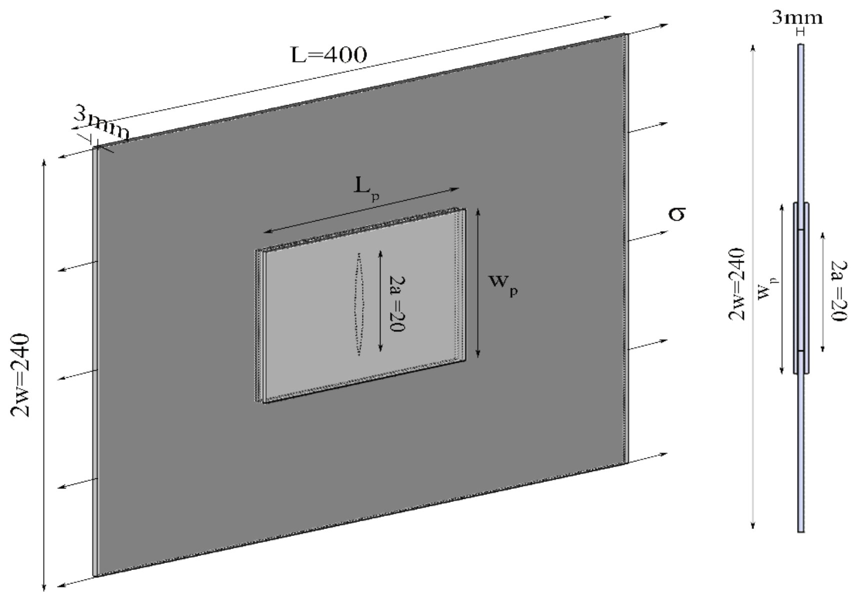

Fig. 8 Geometric properties of double-sided patch (symmetric)

3.2 Verification of the model

In order to evaluate the procedure, a static monotonic load of magnitude 70 MPa has been assigned to the parent material, depicted in Fig. 5. Then, the stress intensity factor has been calculated by XFEM and compared with three well-known theoretical relations of the literature. To do so, the proposed relations of Anderson (2005), Rooke and Cartwright (1976), and Aliabadi and Lopez (1996), have been selected and then have been reflected in Eqs. (1)-(3), respectively. The comparison of the result of XFEM and the mentioned equations are tabulated in Table 1.

$$K_I = \sigma\sqrt{\pi a \sec\frac{\pi a}{2w}}\left[\,?\; - 0.025\left(\frac{a}{w}\right)^2 + 0.06\left(\frac{a}{w}\right)^4\right] \tag{1}$$

$$K_I = \frac{\sigma\sqrt{\pi a}\left[\,?\; - \left(\frac{a}{2w}\right) + 0.326\left(\frac{a}{w}\right)^2\right]}{\sqrt{1-\frac{a}{w}}} \tag{2}$$

$$K_I = \sigma\sqrt{\pi a}\left[\begin{array}{l} 1 + \frac{0.43a}{w} + 0.491\left(\frac{a}{w}\right)^2 + 7.125\left(\frac{a}{w}\right)^3 \\ -28.403\left(\frac{a}{w}\right)^4 + 59.583\left(\frac{a}{w}\right)^5 - 65.278\left(\frac{a}{w}\right)^6 + 29.762\left(\frac{a}{w}\right)^7 \end{array}\right] \tag{3}$$

As it can be seen in Table 1, it is apparent that the deviations between the relations proposed in the literature and the XFEM solution are negligible. Hence, the model could be used to model the retrofitting performance of the three mentioned crack arrest methods. The reason behind the choice of stress intensity factor for validation is the existence of close relation between fatigue and K_{IC}. In the present study, since $R \neq 0$, the Forman's formulation (Eq. (4)) was used for modelling the fatigue resistance of models (Mínguez 1994).

$$\frac{da}{dN} = \frac{C\,\Delta K^m}{\left[(1-R)(K_C - K_{max})\right]} \tag{4}$$

where C and m are empirical material constants, which can be found either from experiments or literature. In the present study, these constants were extracted from the (Stephens *et al*. 2000).

Table 1 Comparison between mode I stress intensity factors $\left(\mathrm{MPa}\sqrt{\mathrm{mm}}\right)$

K_{IC} calculated from Eq. (1)	K_{IC} calculated from Eq. (2)	K_{IC} calculated from Eq. (3)	K_{IC} calculated from XFEM
393.843	392.904	408.124	396.354

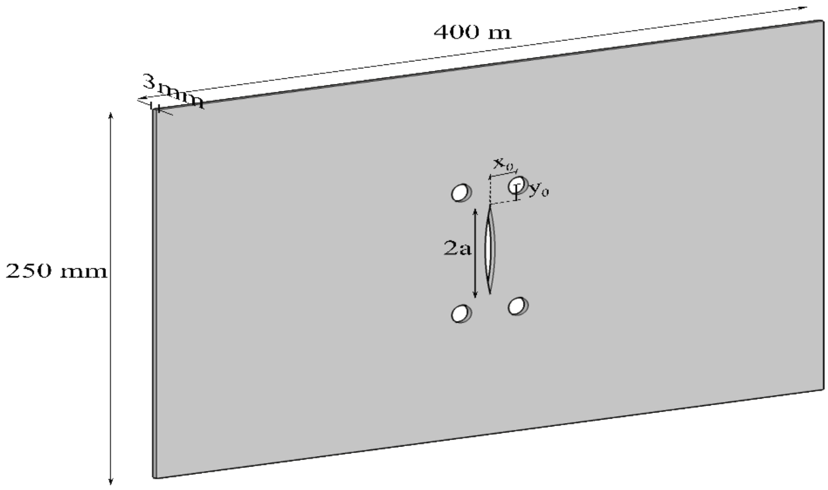

Fig. 9 A center crack with symmetric stop holes

4. Results and discussions

In the present paper, the three main categories of crack arrest methods have been numerically studied. To do so, the retardation of drilling symmetric stop holes (Fig. 9) and single stop hole (Fig. 10), double-sided metal or composite patch (Fig. 8), single-sided metal or composite patch (Fig.7) have been compared.

4.1 Drilling stop-hole

The use of stop-hole technique is one of the most commonly used crack arrest methodology. This method could be categorized into two main group i.e., drilling symmetric flank holes or drilling stop-hole at the tip of the crack. A detailed literature review has been presented in section 2.1. In the present study, in accordance with the work of Ayatollahi and his co-workers (Ayatollahi *et al.* 2014), and Chen and his co-workers (Chen *et al.* 2011), it was assumed that the optimum place for the flank holes (Fig. 9) are where the X_0 and Y_0 are about 0.15 times the crack length and 0, respectively. The other variable could be the diameter of the hole, which is assumed to be 3 mm, based on the study of (Waheed *et al.* 2004).

Fig. 11 reflects the retrofitting performance of stop-hole technique. Besides, the figure makes it possible to compare the crack-arrest ability of the flank holes with crack-tip holes. As it is apparent in Fig. 11, the flank holes are more efficient than the crack tip holes. In other words, the flank holes could enhance the fatigue retardation performance of the system up to 50% more than crack tip stop-hole. Actually, the stop-hole technique leads to an increase of crack tip radius. This causes the stress field to decrease such that more energy is needed for crack nucleation. Therefore, the retardation occurs by drilling stop-hole (Pedersen 2004, Makabe *et al.* 2009).

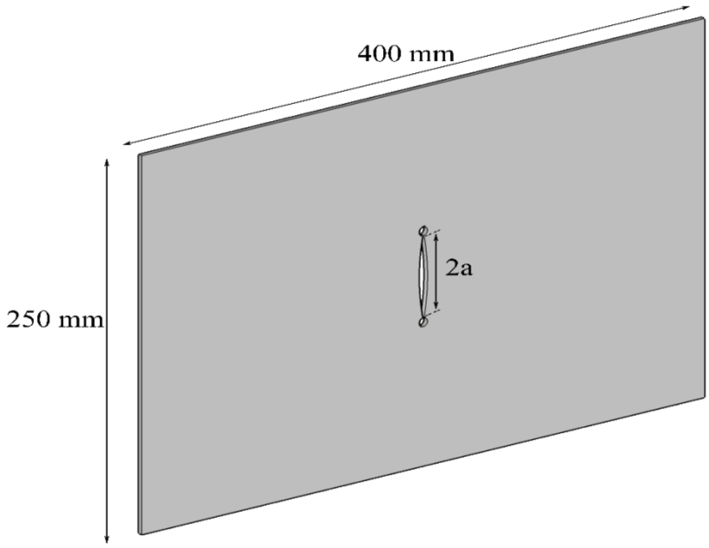

Fig. 10 A center crack with stop holes on its tips

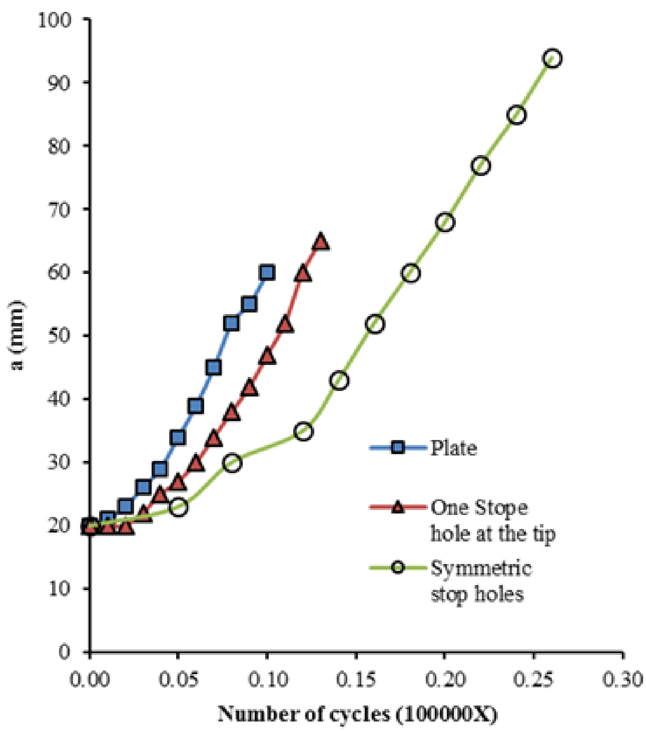

Fig. 11 A center crack with stop holes on its tips

4.2 Effect of CFRP patches

Durability, low self-weight, high elastic modulus, and easy installation are of most common reasons of paying attention to carbon fiber reinforced composites for retrofitting purposes. Moreover, the conventional methods such as welding a metal patch or drilling stop-hole could increase the self-weigh of the structure and could weaken the cross section of the element, respectively (Colombi and Fava 2012, Colombi and Fava 2015, Colombi *et al.* 2015, Colombi and Fava 2016). On the other hand, there are some drawbacks regarding the use of CFRP. For instance, the adhesive joint is sensitive to high temperature, exposure to moisture and water (Colombi and Fava 2016). In addition, when the carbon fibers are in contact with steel surface, a galvanic cell is obtained, which increases the risk of galvanic corrosion (Colombi and Fava 2016). Actually, by means of CFRP, crack arrest uses three ways to enhance the fatigue life of the structures including reduction of the effective stress range in the vicinity of the crack tip, bridging the stresses between the crack flanks, and promotion of crack closure (Colombi and Fava 2016). The mechanical properties of CFRP, considered in the present study are based on the data sheets provided by the local CFRP providers as $E_1 = 135\ GPa$, $E_2 = E_3 = 9\ GPa$, $\nu_{12} = 0.3$, $G_{12} = G_{13} = 5\ GPa$, $G_{23} = 8\ GPa$, $\nu_{13} = 0.3$, and $\nu_{23} = 0.02$. In addition, the optimum geometric properties of the patches were extracted from the study of (Makabe, Murdani et al. 2009). The geometric properties of the CFRP patches are shown in Table 2. It is worth noting that in the present study, both one-sided and double-sided patching were considered. Fig. 12 shows the results corresponding the retrofitting by means of CFRP patches.

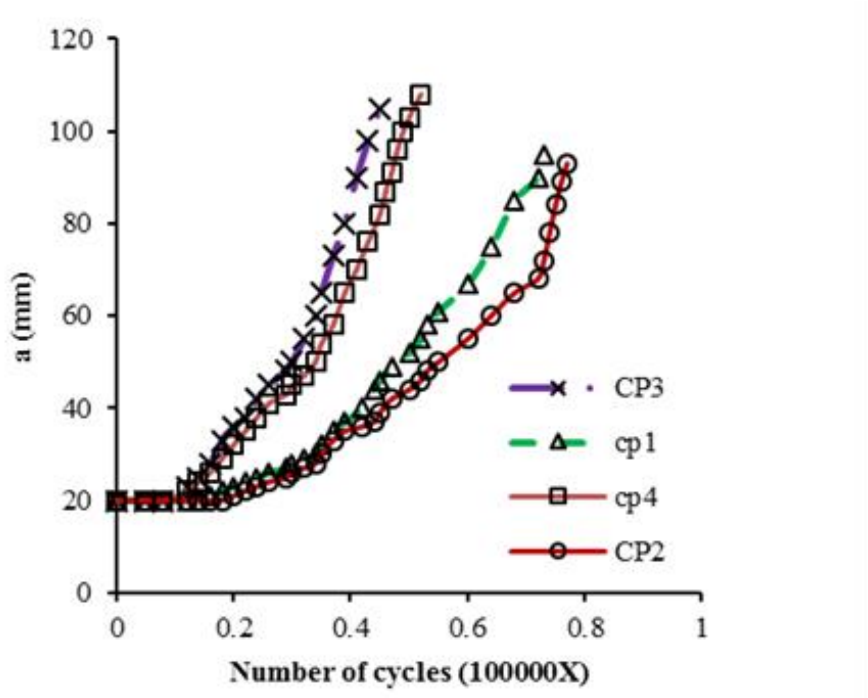

Fig. 12 Effect of CFRP patches on fatigue life

Table 2 Geometry of the composite patches (mm)

Sample	Length (L_P)	Width (W_P)	Thickness (t_P)
CP1	300	250	2
CP2	300	250	2×1
CP3	300	150	2
CP4	300	150	2×1

As it can be seen from Fig. 12, the increase of patch width enhanced the retarding performance of the system. Besides, the use of double-sided patching with the same equivalent thickness yielded better results than the system with single-sided patch. In other words, the retardation of double-sided patches was averagely 20% higher than single-sided patch.

4.3 Effect of steel patches

One of the traditional methods of crack arrest is the use of welded metal patch. In this method, load carrying capacity of the system consists of two parts including the patch and the damaged member. However, thermal and residual stresses, due to welding as well as the increase of self-weight, are notable. In the present study, it is assumed that the metal patch material is identical to the parent material and the thickness of the patch equals to the thickness of the damaged member, as recommended by (Marazani *et al.* 2017). Table 3 reflects the geometric properties of welded metal patches.

Fig. 13 shows the effect of welded metal patch on fatigue life of a damaged element. As it can be observed, patches with W_P of 50 and 60 mm showed better performance that those with W_P=40 mm. Actually, the width of 50 mm was the optimum patch width. In addition, symmetric installation of double-sided metal patches enhances the performance of the equivalent single-sided system up to 15%.

Fig. 14 presents a comparison of the three mentioned categories of crack arrest methods. It is clear that retrofitting by CFRP patches could lead to a better fatigue endurance limit. Besides, this method of crack arrest is easier to install, lighter, and more durable.

Table 3 Geometry of welded metal patches (mm)

Sample	Length (L_P)	Width (W_P)	Thickness (t_P)
WP1	240	40	3
WP2	240	50	3
WP3	240	60	3
WP4	240	50	2×1.5

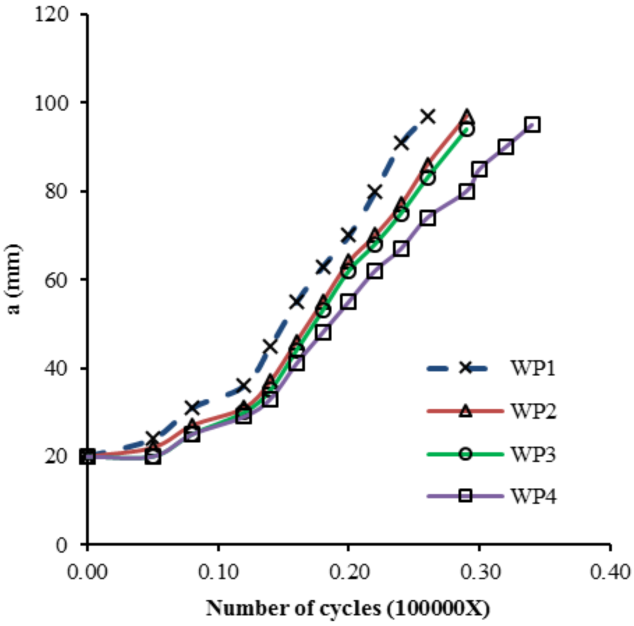

Fig. 13 Effect of welded metal patches on fatigue life

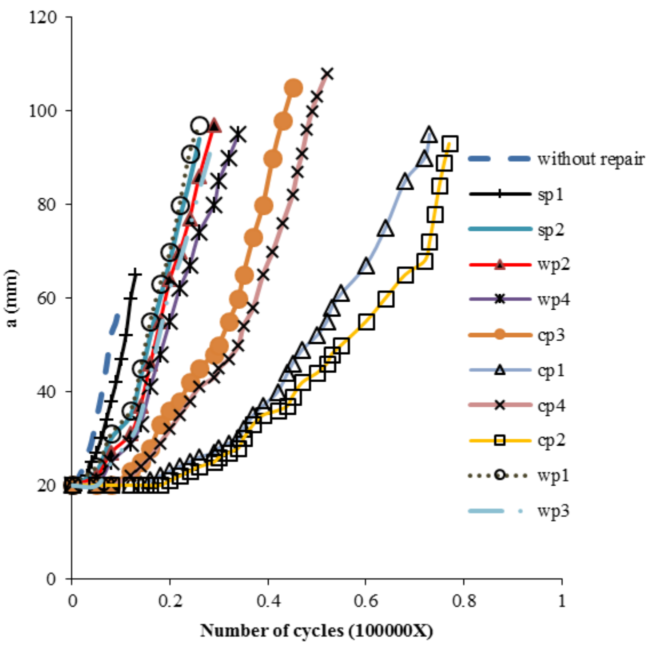

Fig. 14 A comparison between stop-hole technique, welded metal patch, and CFRP patch

5. Conclusions

In the present study, a comprehensive review has been presented about the three main methods of crack arrest including stop-hole technique, the use of metal, and CFRP patches. Besides, a numerical study has been conducted by means of extended finite element method in order to numerically assess and compare these three methods. Generally, for crack arrest purposes, the composite patches are better than welded metal patches, and welded metal patches are better than drilling stop-holes. However, some key points should be considered in practical situations, such as galvanic corrosion, self-weight of the structure, and installation. Symmetric flank holes showed averagely 50% better retardation performance than single stop-holes in a plate with central crack. However, drilling flank holes could weaken the cross section more than a single hole. In addition, the use of double-sided CFRP patches averagely enhanced the retardation of fatigue crack growth by 20% compared to the single-sided CFRP patch. However, the condition of installation of the plates should be considered. In comparison with single-sided metal patch system, the use of symmetric metal patches could decrease the fatigue crack growth rate of the system by 15%. Of course, it should be mentioned that in cases in which the self-weight plays an important role in loads, the use of symmetric patches could worsen the condition. It should be noted that symmetric CFRP patches improved the fatigue endurance of the system by 70% compared to symmetric welded metal patch system. Besides, symmetric CFRP patches enhanced the fatigue behavior of the system by about 70% compared to symmetric flank holes. It is also worth mentioning that symmetric welded metal patches improved the fatigue life of the system by about 21% in comparison with symmetric flank holes.

Acknowledgments

This work was supported by Shahid Rajaee Teacher Training University.

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