ORIGINAL

Vipin Sukumara Pillai[iD] · **Athanasios Kolios** · **Seng Tjhen Lie**

Failure assessment of cracked uni-planar square hollow section T-, Y- and K-joints using the new BS 7910:2013+A1:2015

Abstract This paper covers the validation of standard safety assessment procedure in the new BS 7910:2013+A1:2015 for cracked uni-planar square hollow section (SHS) T-, Y- and K-joints using the finite element analyses. The procedure is based on the failure assessment diagram (FAD) method. A completely new and robust finite element mesh generator is developed, and it is validated using the full-scale experimental test results. FAD curves are constructed using the elastic J-integral (J_e), the elastic-plastic J-integral (J_{ep}) and the plastic collapse load (P_c) values calculated using the 3D cracked models of the joints. The results reveal that the standard Option 1 FAD curve of the new BS code is not always safe in assessing the safety and integrity of cracked uni-planar SHS joints. Therefore, a penalty factor of 1.2 for plastic collapse load is recommended to move all the constructed Option 3 FAD curves above the standard Option 1 curve. The new Option 3 FAD curves are found to generate optimal solutions for cracked uni-planar SHS T-, Y- and K-joints.

List of symbols

J_e	Elastic J-integral
J_{ep}	Elastic-plastic J-integral
K_I	Stress intensity factor
K_{IC}	Fracture toughness
K_r	Fracture ratio using stress intensity factor
L_r	Ratio of applied load to plastic collapse load
P_a	Applied load
P_c	Plastic collapse load
σ_{ref}	Reference stress
σ_y	Yield stress

V. Sukumara Pillai (✉)
Offshore Energy Engineering Centre, Cranfield University, Cranfield MK43 0AL, UK
E-mail: Vipin.Sukumara-Pillai@cranfield.ac.uk
Tel: +441234754855

A. Kolios
University of Strathclyde, Glasgow G1 1XQ, UK

S. T. Lie
School of Civil and Environmental Engineering, Nanyang Technological University, 639798 Singapore, Singapore

1 Introduction

Several assessment methods based on fracture mechanics have been developed during the last 40 years. The widely used assessment technique that is followed in recent times is the failure assessment diagram (FAD) approach. The basis of the FAD approach was originally developed by Dowling and Townley [1]. According to this approach, a structure can fail by either of two mechanisms, namely brittle fracture and plastic collapse. A design curve labelled as failure assessment curve is used to interpolate between the two failure criterions as shown in Fig. 1. The integrity of the structure is determined by the relative position of the assessment point on the FAD. The relative position is derived from two separate set of calculations covering both brittle fracture and plastic collapse. The final assessment procedure is quite straightforward, i.e. if the relative position of the point is inside the FAD curve, the structure is considered to be safe.

However, if the relative position of the point is outside the FAD curve, the structure is considered to be unsafe. The reliability of the result produced by FAD approach depends on the accuracy by which the failure assessment curve is plotted which in turn depends upon the structural geometry, nature of loading and the crack size. Complex three-dimensional geometry makes it challenging to create the FE mesh model of a cracked SHS joint by using commercial FE softwares. The current study develops a new FE mesh generator in order to construct reliable FAD curves. The details of the new FE mesh generator and its validation using the full-scale experimental test results are explained in the subsequent sections.

2 The new BS 7910:2013+A1:2015 approach

BS 7910:2013+A1:2015 [2] specifies the guidance for assessing the acceptability of defects in welded structures based on FAD method. It specifies three levels of assessment. The three levels are Option 1, Option 2 and Option 3. The Option 1 curve of curve in BS 7910:2013+A1:2015 [2] is given by
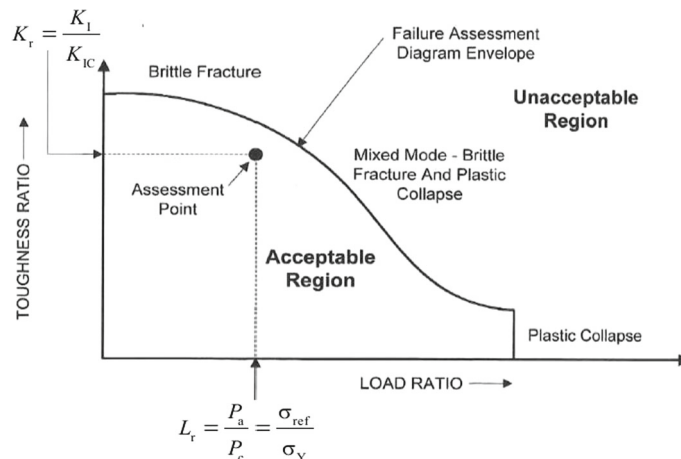
$$K_r = (1 - 0.14L_r^2)[0.3 + 0.7\exp(-0.65L_r^6)] \tag{1}$$

where

$$K_r = \frac{K_I}{K_{IC}} = \sqrt{\frac{J_e}{J_{ep}}} \tag{2}$$

$$L_r = \frac{\text{applied load to the flawed structure}}{\text{plastic collapse load of the flawed structure}} \tag{3}$$

The fracture occurs when the elastic-plastic value of crack tip driving force reaches a critical value corresponding to the fracture toughness and is given by $\sqrt{EJ_{ep}} = K_{IC}$ [3]. Therefore, Eq. (2) can be modified as

Fig. 1 Flaw assessment using FAD approach
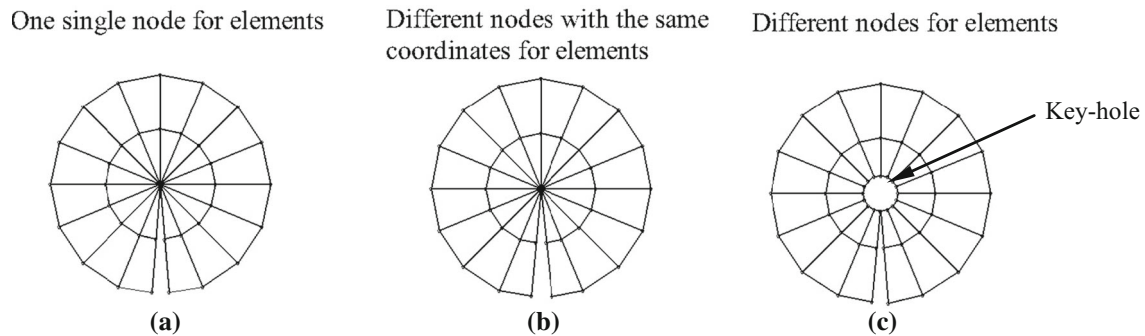
Fig. 2 Three different methods used to model the crack tip

$$K_{r} = \frac{K_{I}}{K_{IC}} = \sqrt{\frac{J_{e}}{J_{ep}}} \tag{4}$$

where J_e = elastic J-integral and J_{ep} = elastic-plastic J-integral. Option 1 is intended for general applications and is independent of the structural geometry and the material stress–strain curve. It was developed from extensive experimental databases of laboratory specimens [4]. Option 2 is more accurate than Option 1 with respect to flaws in stress gradients and the treatment of residual stresses. Unlike Option 1, Option 2 requires simple data and analysis. The drawback with Option 2 is that its scope is restricted to limited ductile tearing. Therefore, to give more accurate predictions of structural behaviour, Option 3 assessment is used. Option 3 is an advanced assessment approach requiring detailed data, computer analysis and considerable technical knowledge and expertise in assessment procedures. In Option 3 assessments, FAD curves are constructed based on the detailed information of stress–strain curves of the materials. It is significantly relevant to materials having a high strain-hardening capacity and where an analysis of stable crack extension is needed. It is suitable for ductile materials that exhibit stable tearing, e.g. austenitic steels and ferritic steels on the upper shelf.

The Option 1 and Option 2 FAD curves of BS 7910:2013+A1:2015 [2] are intended for all types of structures and may not essentially provide optimal solutions for different types of structures such as cracked uni-planar SHS T-, Y- and K-joints. Option 3 FAD curve gives the most accurate representation of the structural behaviour of a component [2]. There are many existing structures such as bridges, buildings and offshore structures which are fabricated using square hollow section (SHS) joints. In this study, Option 3 FAD curves are constructed for cracked uni-planar SHS T-, Y- and K-joints to validate the standard Option 1 curve of BS 7910:2013+A1:2015 [2] and to recommend optimal solutions that can safely be used to assess cracked uni-planar SHS T-, Y- and K-joints.

3 New finite element mesh generator and validation

In order to assist in safety assessment of cracked uni-planar square hollow section (SHS) welded joints, the current study develops an entirely new and robust finite element (FE) mesh generator. The nature of mesh geometry around the crack tip is the most pivotal feature in the numerical modelling of flawed structures [5]. Improper modelling of crack tip will lead to untimely termination of elastic-plastic analyses. In elastic analyses, all nodes at the crack tip are normally tied and the mid-side node of the crack element is moved to the quarter (1/4) point position to produce a $1/r^{1/2}$ strain singularity. A typical construction of the crack tip elements in elastic analyses is shown in Fig. 2a. In case of elastic-plastic analyses, a small plastic zone is formed in the crack tip region. Therefore, the $1/r^{1/2}$ strain singularity is no longer applicable at the crack tip region. In such cases, all elements surrounding the crack tip region create a $1/r$ strain singularity, which relates to the actual crack tip strain field for a totally plastic material.

Broadly, two approaches are used to model crack tip elements for elastic-plastic analyses. Figure 2b illustrates the first method where the crack tip nodes are coincident and untied. The drawback for using this approach is the blunting at the crack tip caused due to the formation of large strains during the elastic-plastic analyses. This can be ignored if the deformation at the crack is comparatively small [6]. However, for large-scale deformations, the collapse of the crack tip elements takes place leading to inaccurate elastic-plastic J-integral

(J_{ep}) outcomes. Moreover, there are convergence issues associated with the large-scale plastic deformation analyses. Anderson [7] introduced the concept of using a keyhole, depicted in Fig. 2c, for which there is a finite radius for the plastic zone located at the crack tip. Modelling using keyhole ensures the convergence of solutions for large-scale plastic deformation as well as it prevents the collapse of elements adjacent to crack tip region. The selection of finite radius for the keyhole requires special attention. Very small values of finite radius lead to collapse of the adjacent elements around crack tip while the large values lead to inaccurate results since the value must be within the plastic zone. For the current research works, the value of keyhole radius is chosen according to the provisions specified in API RP579 [8], whereby it is at least five times smaller than the tip radius in the distorted state. The value is set as a variable so that the user is able to vary it appropriately for each case. A value of 0.1mm is found to be sufficient to avoid the collapse of elements at the crack tip for the large-scale nonlinear deformation. The authors recommend a finite radius of keyhole from 0.05mm to 0.15mm with 0.1mm as the most appropriate value for load values in the range of 1000 kN.

The FE mesh of cracked SHS T-, Y- and K-joints is generated block by block using different mesh zones. The zone containing the parent crack block is generated first, and subsequently, adjacent zones are created which are merged finally to form the cracked uni-planar SHS T-, Y- and K-joints. The sequence to form the parent brace for SHS joint is depicted in Fig. 3. The parent brace part generated is transformed to complete cracked uni-planar SHS T-, Y- and K-joints by adding the chord parts on both sides (Fig. 4). The new FE mesh generator is versatile enough to model cracks of any arbitrary dimensions. The concept of using keyhole for elastic-plastic analysis is effectively incorporated in the new FE mesh generator. The usage of only one type of element, i.e. 20-node hexahedral element, eliminates the compatibility issues associated with mesh modelling. The 'spider web' configuration which is the most effective mesh design for the crack tip region enables a smooth conversion from a fine mesh at the crack tip region to a coarser mesh away from high stress concentration region. Mesh refinement and zoning techniques are extensively used in the new FE mesh generator so that it is robust to model different types of uni-planar and multi-planar SHS welded joints with and without cracks. Another feature of the new FE mesh generator is the fast generation of different types of cracked and uncracked models. For example, a typical cracked uni-planar SHS T-joint with 15,000 elements can be generated within 3 min.

The validations for the results obtained using the new FE mesh generator are carried out using the results from both full-scale experimental tests as well as with the prevailing commercial softwares. In addition, aspects such as mesh convergence, mesh refinement and aspect ratio check are diligently checked to ensure the quality of the mesh. As an example, the elastic J-integral results from the new FE mesh generator are compared with the results produced from the mesh generated using FEACrack^{TM} software [9] (Fig. 5). The maximum percentage difference among both cases is 0.09% at the deepest point of the crack and 7.89% at the crack ends. The variation trend observed for J-integral values with respect to different crack front angle values compliments each other. In addition, convergence of solutions reconfirms the reliability of using the new FE mesh generator. The experimental test rigs for cracked uni-planar SHS T-, Y- and K-joints are shown in Fig. 6. The load–displacement curves point out the analogous trends between experimental and numerical models (Fig. 7). The tendency of the load–displacement curve obtained from numerical analyses being slightly above the experimental curve is most visible in the case of SHS K-joint. This is due to the fact that the stress–strain curve used for numerical analyses may not be exactly same as the actual condition in the full-scale experimental tests. For instance, the stress–strain curve at the corner of the SHS joints is generally higher due to the strain hardening in the corner. It is also observed that the post-peak unloading curves observed in the experimental results deviate from numerical curves. This deviation does not affect the accuracy of the results produced using the new FE mesh generator as there is good agreement between the experimental and numerical results for the load–displacement curves in the plastic collapse region. Detailed discussion on the experimental test setup and the loading protocol is outside the main purview of the current manuscript. Further in-depth discussion about the validation of the new FE mesh generator is also available in other previously published works of the authors [10–14].

4 FADs of cracked uni-planar SHS joints

The validated new FE mesh generator is subsequently used for fracture analysis of cracked uni-planar SHS T-, Y- and K-joints. The material considered in the current study is BS4360 structural steel of Grade 50D, and the stress–strain curve of the material is shown in Fig. 8. On completion of both elastic and elastic-plastic analyses using the ABAQUS software [15], elastic (J_e) and elastic-plastic J-integral (J_{ep}) values are obtained,

Crack block

Plate

Curve T-butt to
Form the brace
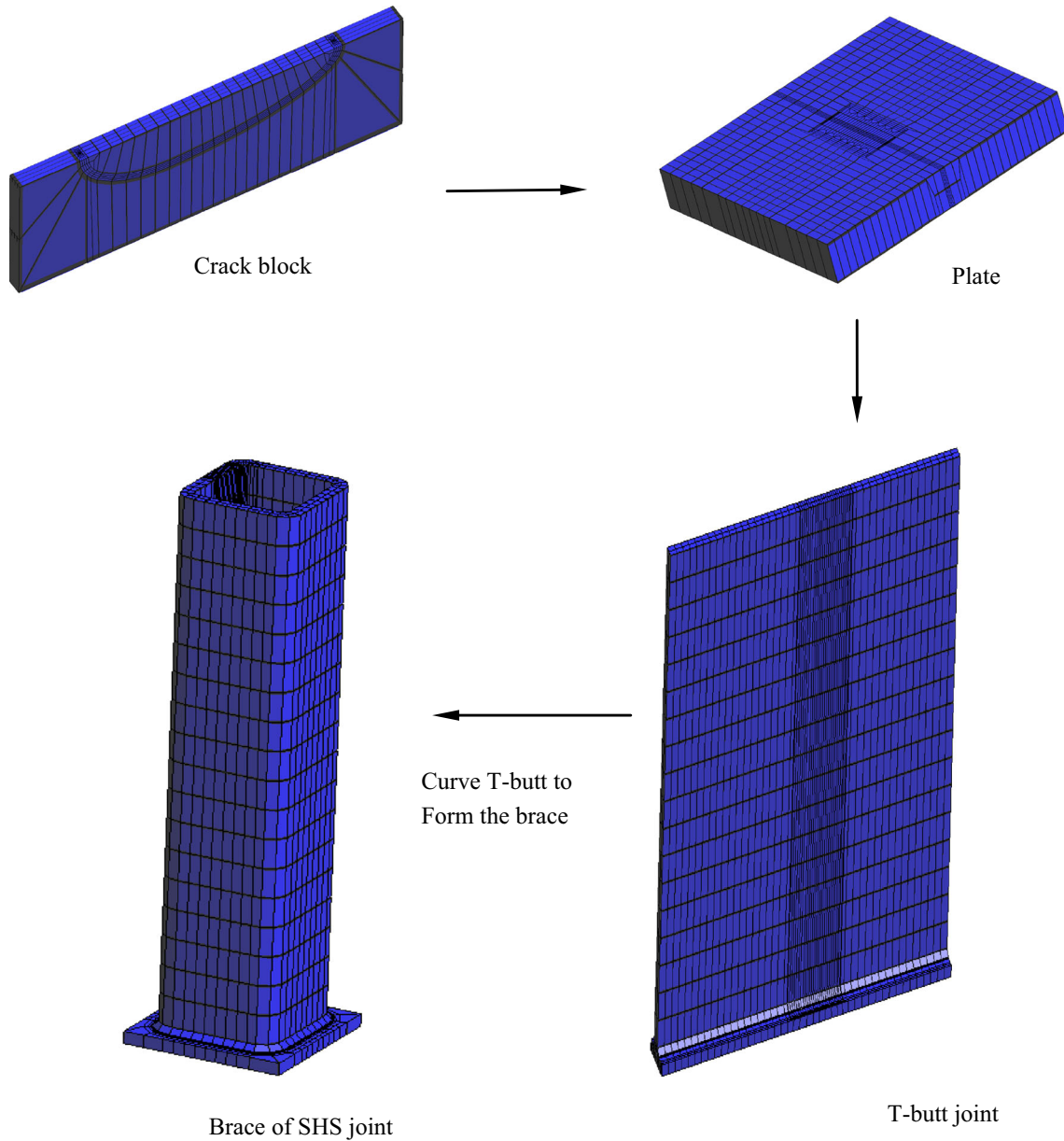
Brace of SHS joint

T-butt joint

Fig. 3 Sequence to form the parent brace of SHS T-joint

respectively. The J-integral is calculated using the virtual crack extension (VCE) technique which is built in ABAQUS software [15]. It interprets the J-integral as a function of location along the crack front which provides the reduction in total potential energy of the loaded structure due to an increase in the crack opening area at that same position on the crack front.

ABAQUS software [15] formulates this as follows:

$$-\delta P = \int_{s} J(s) \cdot \delta l(s) \mathrm{d}s \tag{5}$$

where δP is the change in the structure's total potential energy, s is the coordinate which identifies location along the crack front, $J(s)$ is the J-integral value, and $\delta l(s)$ is the advance of the crack front normal to itself and in the local plane of the crack at this point. The value of $J(s)$ and the VCE are then interpolated from the value at crack front nodal position through the identical order of interpolation as used in the elements adjoining the crack front. Thus, Eq. (5) becomes, in the FE model, a set of equations which relate the set of total potential
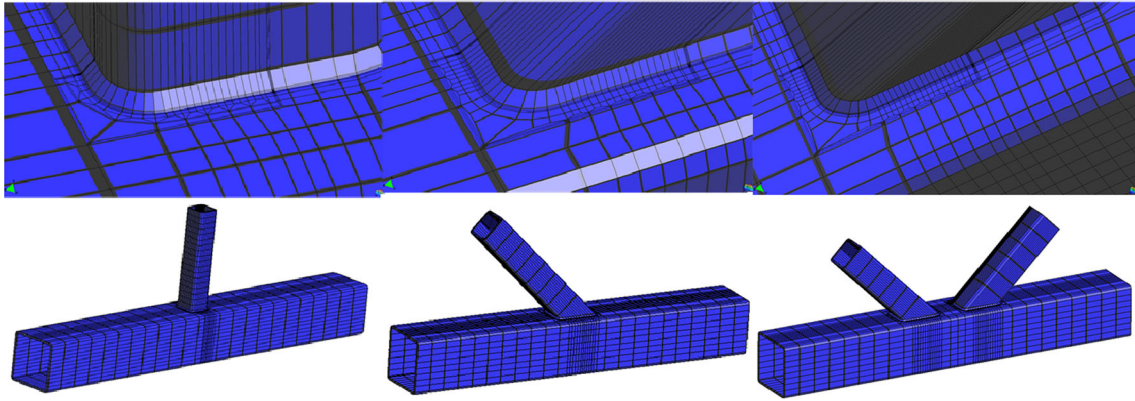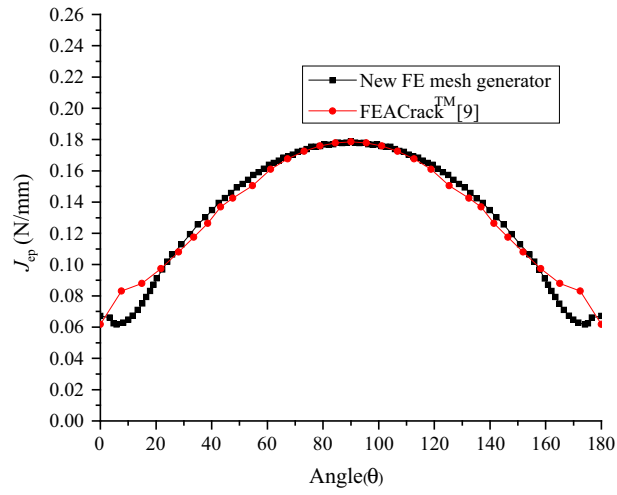
Fig. 4 Cracked SHS T-, Y- and K-joints

Fig. 5 Comparison of J-integral values obtained using new FE mesh generator and FEACrack[TM] [9]

Fig. 6 The experimental test rigs for cracked SHS T-, Y- and K-joints
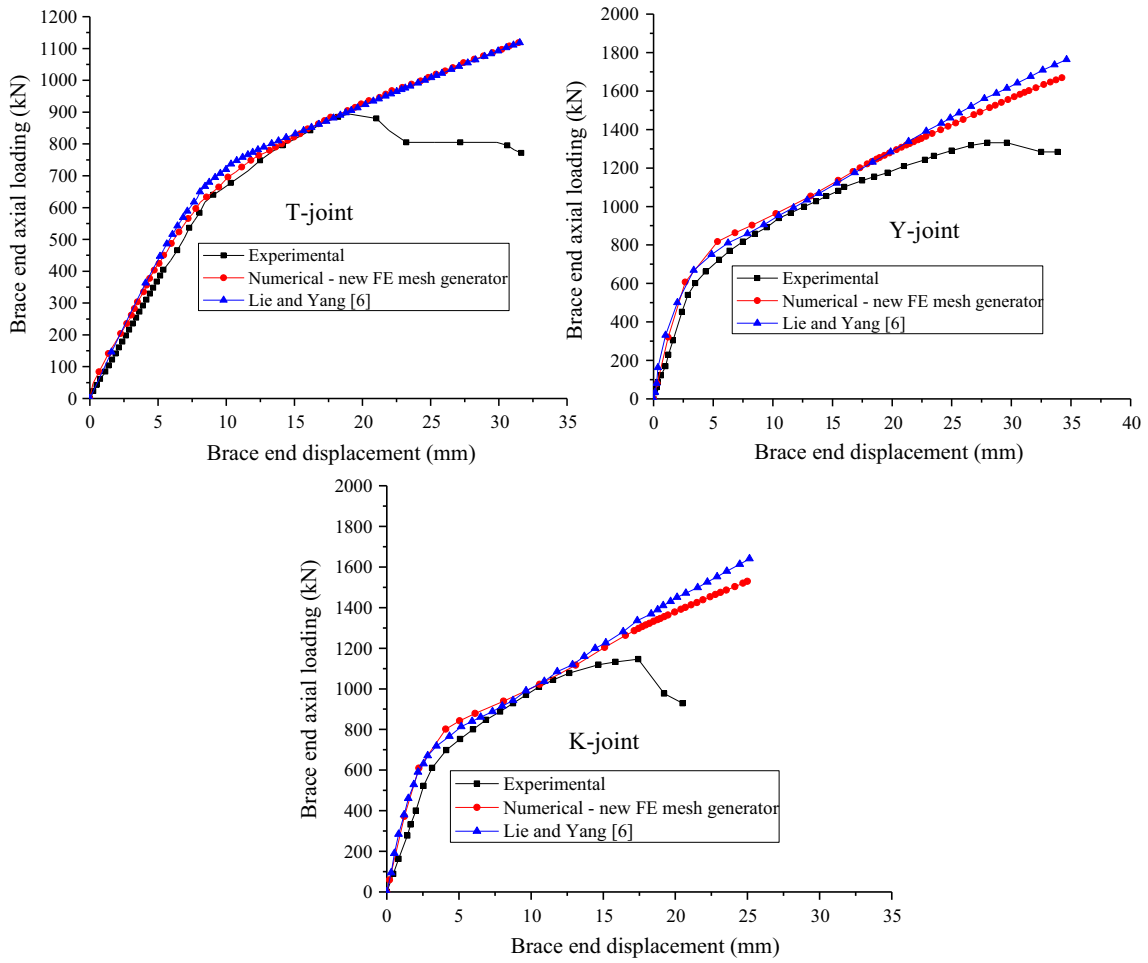
Fig. 7 Comparison of numerical and experimental results for SHS T-, Y- and K-joints
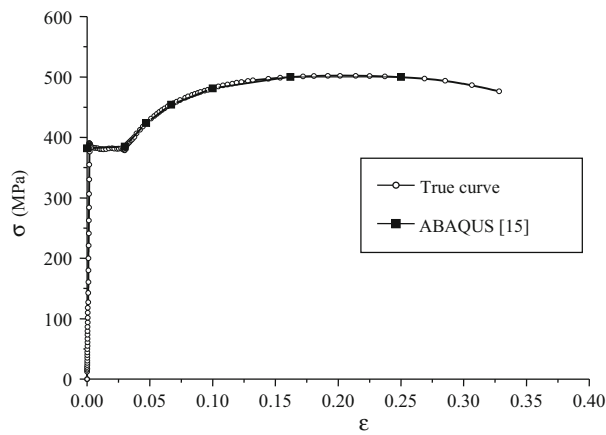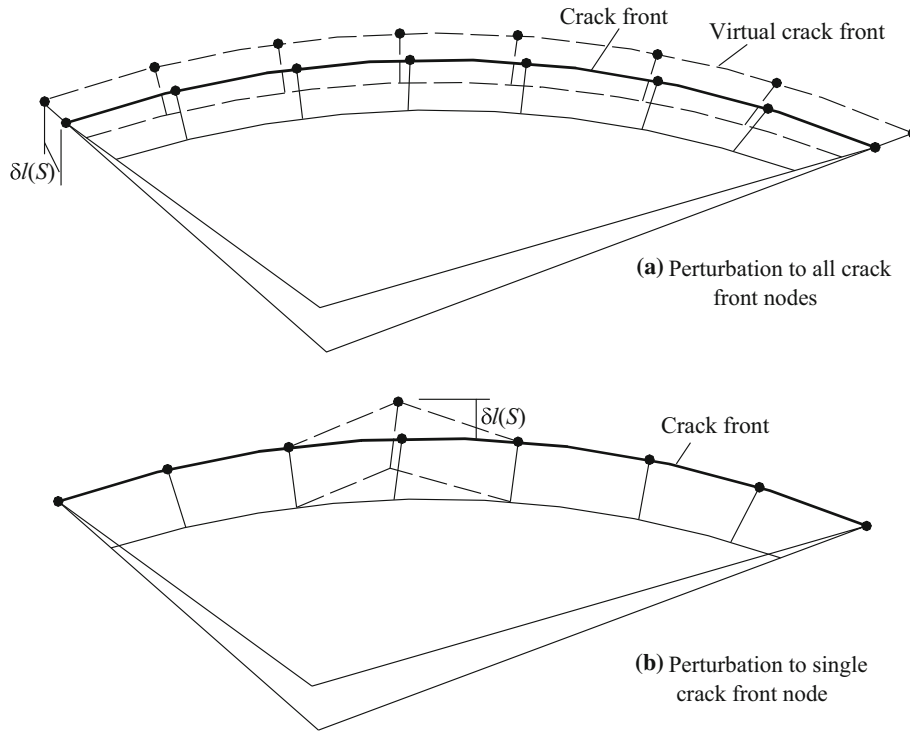

Fig. 8 Stress–strain curve of the BS4360-50D structural steel

Fig. 9 Crack front perturbation by virtual crack extension

energy variations produced by crack advances at each crack front nodal position to the J-integral values of the same crack front nodal positions. After these values are determined, the equations can be solved for these nodal positions values of J-integral. The method is specifically suitable because it is simple to use, cost beneficial and ensures good accuracy [16].

There are two methods for the application of VCE techniques in the 3D settings as illustrated in Fig. 9. In Fig. 9a, all the crack front nodes are perturbed, while in Fig. 9b only one node is perturbed. In the first approach, elliptical crack is reduced to two degrees of freedom by transforming elliptical cracks to be distorted into other elliptical cracks, changing only the size parameters (semi major and minor axes). In the second approach, the local node is disturbed alone leading to a good estimate of the local value of J-integral or stress intensity factors K. This results in the increase in the number of degrees of freedom. For the current study, the second approach (local perturbation) is used to calculate the J-integral along the crack front.

Option 3 FAD curves are constructed for cracked uni-planar SHS T-, Y- and K-joints using the elastic (J_e) and elastic-plastic J-integral (J_{ep}) values and the plastic collapse load (P_c). The P_c load is determined using the twice elastic compliance (TEC) criterion. Several previous studies used the TEC criterion to determine the P_c load of cracked tubular joints [17,18]. This plastic criterion is described in ASME VIII Division 2 [19] as the twice elastic slope (TES) criterion. The TEC criterion is established on the load–deformation response of a structure in the plastic analysis as shown in Fig. 10. The P_c load is the load corresponding to the intersection of the load–deformation curve and the twice elastic compliance line. The twice elastic compliance line starts from the origin of the load–deformation curve and has twice the slope of the initial elastic response, which is calculated using the equation

$$\tan \varphi = 2 \tan \theta \qquad (6)$$

where φ and θ are the angles measured from the load axis as shown in Fig. 10.

Upon obtaining the elastic (J_e) and elastic-plastic J-integral (J_{ep}) values and the plastic collapse load (P_c) values, Option 3 FAD curves are constructed for cracked uni-planar SHS T-, Y- and K-joints. It is observed that some of the constructed curves tend to fall below the standard Option 1 curve of BS 7910:2013+A1:2015 [2] (Fig. 11). This is especially prominent towards the right side of the FAD curves which is near to the plastic collapse region in the standard Option 1 curve of BS 7910:2013+A1:2015 [2]. This trend is not desirable as it is clear from Fig. 1 that the integrity of the structure is estimated by the relative position of the assessment point on the standard FAD curve. Therefore, if an assessment point is located in the intermediate region (the
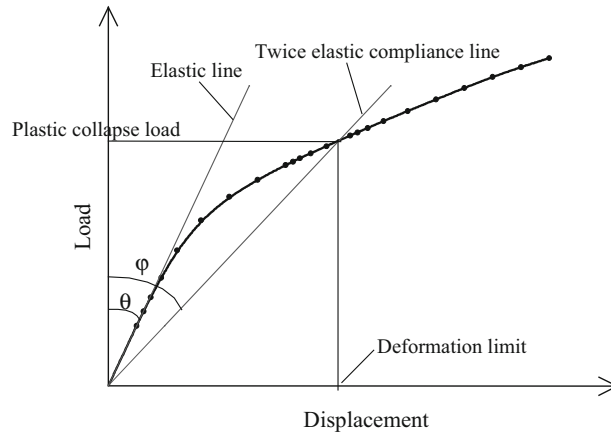
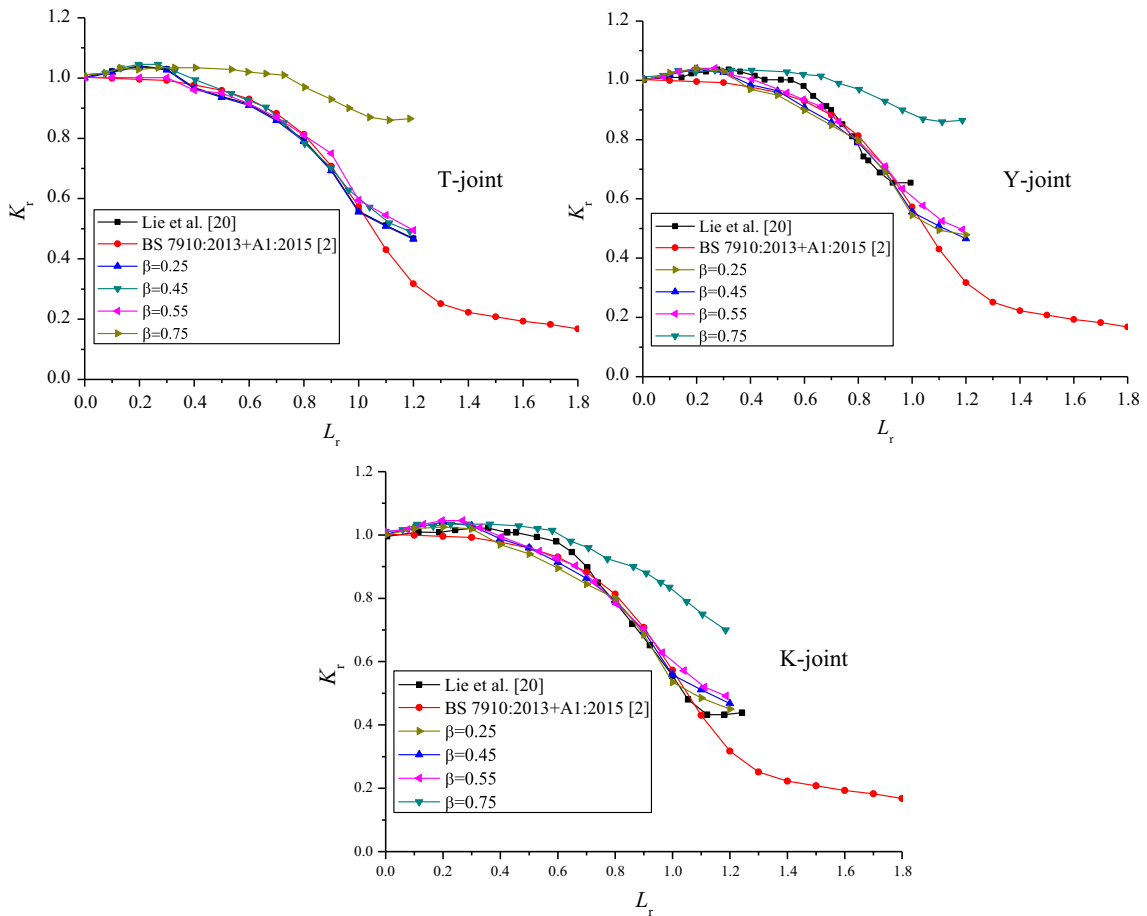**Fig. 10** Twice elastic compliance criterion

Fig. 11 FAD curves for cracked uni-planar SHS T-, Y- and K-joints

region below the standard curve and above the constructed curves in Fig. 11), it may be assumed to be safe, but it may not be truly safe [6]. A straightforward approach to solve this is by introducing a penalty factor for plastic collapse load which is described in following paragraph. The results also reveal that the constructed FAD curves for cracked uni-planar SHS T-, Y- and K-joints with low brace to chord width ratio (β) appear to fall below the Option 1 curve of BS 7910:2013+A1:2015 [2] when compared to the models with higher β ratio.
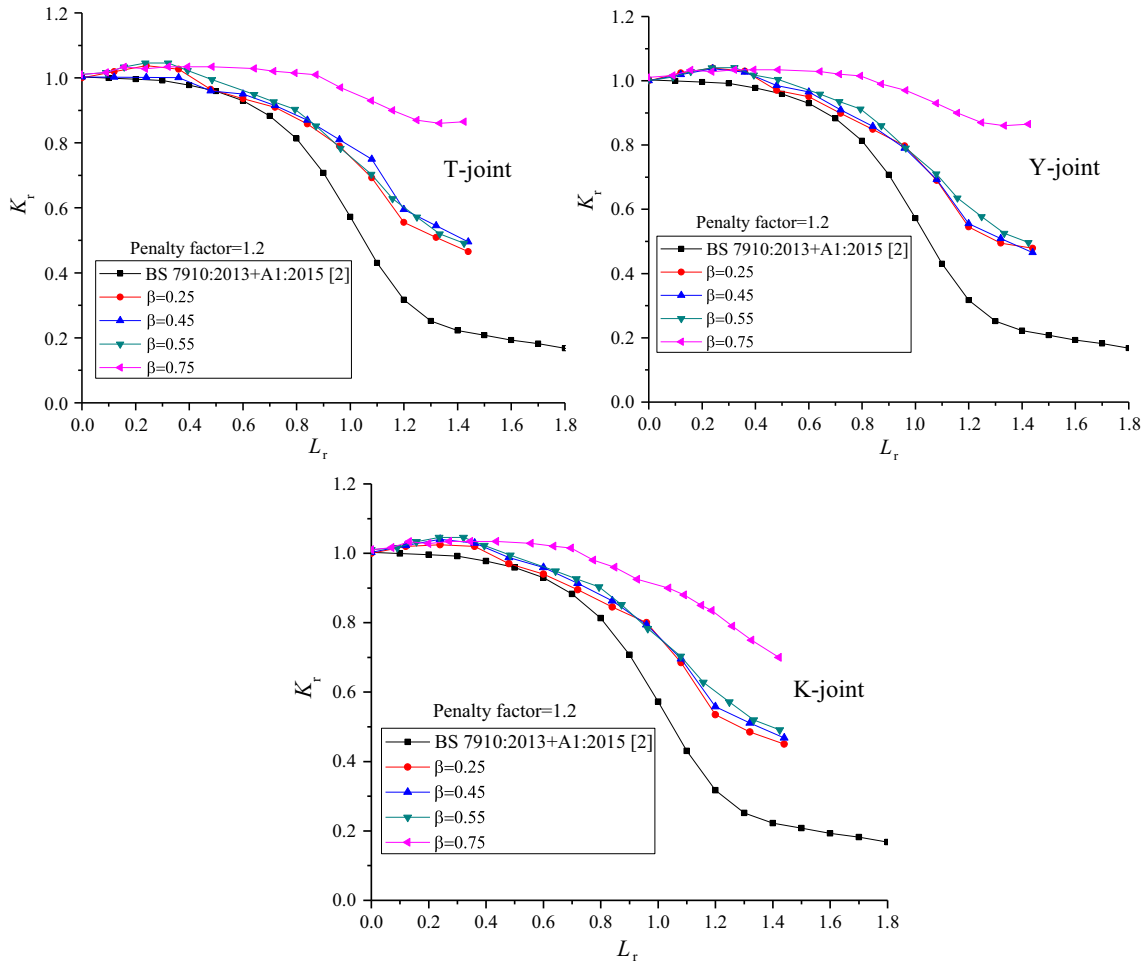
Fig. 12 Optimized FAD curves for cracked SHS T-, Y- and K-joints with a penalty factor of 1.2

This is attributed to increasing plastic collapse load of the uni-planar SHS T-, Y- and K-joints with increasing value of β. It is to be noted that the curve shown in Fig. 11 from Lie et al. [20] is based on the previous version of codes as currently there are no published works depicting the FAD curves for cracked uni-planar SHS T-, Y- and K-joints using the latest BS 7910:2013+A1:2015 [2].

In order to obtain a conservative and safe prediction, a penalty factor of 1.20 is recommended for cracked uni-planar SHS T-, Y- and K-joints. The newly proposed penalty factor is introduced to Eq. (3) whereby the plastic collapse load of the flawed structure is divided by a factor of 1.20 so that a conservative value of the plastic collapse load is used to construct the FAD curves. This procedure ensures that there are no more assessment points which are located at the intermediate region (region corresponding to below the standard curve and above the constructed curves in Fig. 11). Figure 12 depicts the constructed FAD curves for cracked uni-planar SHS T-, Y- and K-joints with the newly introduced penalty factor of 1.20. It can clearly be seen that all the newly constructed FAD curves are located above the standard Option 1 curve of BS 7910:2013+A1:2015 [2]. To summarize, in order to assess the safety and integrity of cracked uni-planar SHS T-, Y- and K-joints in practice using the standard Option 1 curve of BS 7910:2013+A1:2015 [2], a penalty factor of 1.20 is recommended to use while calculating the plastic collapse load values, thereby producing optimal solutions.

5 Conclusions

Complex three-dimensional geometry makes it challenging and time-consuming to generate the finite element (FE) mesh models of cracked SHS joints by using commercial FE softwares. In order to assist in failure

assessment of damaged uni-planar SHS T-, Y- and K-joints, the present study develops an entirely new and robust FE mesh generator. Mesh refinement and zoning techniques are extensively used in the new FE mesh generator so that it is robust enough to model different types of cracked uni-planar SHS welded joints within a short period of time. The new FE mesh generator is validated using the full-scale experimental test results as well as with the commercial software results. Subsequently, the highest level Option 3 FAD curves of cracked SHS joints are constructed using the elastic (J_e) and elastic-plastic J-integral (J_{ep}) values and the plastic collapse load (P_c) values. The constructed Option 3 FAD curves are further used to validate the standard Option 1 FAD curve of the BS 7910:2013+A1:2015 [2]. It is found that Option 1 FAD curve of the BS 7910:2013+A1:2015 [2] is not always safe in assessing the safety and integrity of cracked uni-planar SHS T-, Y- and K-joints. For obtaining a conservative safe prediction, a penalty factor of 1.20 is recommended for cracked uni-planar SHS T-, Y- and K-joints. The newly recommended penalty factor is used to modify the plastic collapse load of the cracked T-, Y- and K-joints through dividing by a factor of 1.20 so that a conservative value of the plastic collapse load is used to construct the FAD curves. It can be seen that all the newly constructed FAD curves using the penalty factor are located just above the standard Option 1 FAD curve of the BS 7910:2013+A1:2015 [2]. These new Option 3 FAD curves are able to provide optimal solutions for cracked uni-planar SHS T-, Y- and K-joints.

References

1. Dowling, A.B., Townley, C.H.A.: The effect of defect on structural failure: a two-criteria approach. Int. J. Pre Pip. **3**(2), 77–107 (1975)
2. BS 7910:2013+A1:2015: Guide to Methods for Assessing the Acceptability of Flaws in Metallic Structures. British Standards Institution, London (2015)
3. Zerbst, U., Ainsworth, R.A., Schwalbe, K.H.: Basic principles of analytical flaw assessment methods. Int. J. Pre Pip. **77**(14), 855–867 (2000)
4. Milne, I., Ainsworth, R.A., Dowling, A.R., Stewart, A.T.: Assessment of the integrity of structures containing defects. Int. J. Pre Pip. **32**(1), 3–104 (1988)
5. Lo, S.H., Lee, C.K.: Solving crack problems by an adaptive refinement procedure. Eng. Fract. Mech. **43**(2), 147–163 (1992)
6. Lie, S.T., Yang, Z.M.: Plastic collapse load of cracked square hollow section T-, Y-, and K-joints. J. Offshore Mech. Arct. Eng. Am. Soc. Mech. Eng. **133**(2), 1–10 (2011)
7. Anderson, T.L.: Fracture mechanics, fundamentals and applications, 3rd edn. CRC Press, Boston (2005)
8. API RP579: Fitness-for-Service. American Petroleum Institute, Washington (2007)
9. FEACrack^{TM}: User's manual. Version 3.2, Quest Integrity Group LLC, Seattle (2010)
10. Lie, S.T., Vipin, S.P., Li, T.: New weld toe magnification factors for semi-elliptical cracks in double-sided T-butt joints and cruciform X-joints. Int. J. Fatigue **80**, 178–191 (2015)
11. Vipin, S.P.: Safety and risk assessment of damaged multi-planar square hollow section (SHS) TT-, YT- and KT-joints. Ph.D. Dissertation, Nanyang Technological University, Singapore (2015)
12. Lie, S.T., Vipin, S.P., Li, T.: New reduction factor for cracked square hollow section T-joints under axial loading. J. Constr. Steel Res. **112**, 221–227 (2015)
13. Lie, S.T., Zhao, H.S., Vipin, S.P.: New weld toe magnification factors for semi-elliptical cracks in plate-to-plate butt-welded joints. Fatigue Fract. Eng. Mater. Struct. **00**, 01–13 (2016)
14. Lie, S.T., Vipin, S.P., Li, T.: New reduction factor for cracked square hollow section multi-planar TT-, YT- and KT-joints. Eng. Struct. **139**, 108–119 (2017)
15. ABAQUS: Standard User's Manual. Version 6.5, Hibbett, Karlsson & Sorensen, Inc., Providence (2011)
16. Aliabadi, M.H., Rooke, D.P.: Numerical Fracture Mechanics. Kluwer Academic Publishers, Dordrecht (1991)
17. Stacey, A., Sharp, JV., Nichols, NW.: Static strength assessment of cracked tubular joints. In: Proceedings of the 15th International Conference Offshore Mechanical Arctic Engineering, Florence, pp. 211–224 (1996)
18. Muscat, M., Mackenzie, D., Hamilton, R.: A work criterion for plastic collapse. Int. J. Pre Pip. **80**, 49–58 (2003)
19. Asme VIII Division 2: Rules for Construction of Pressure Vessels. American Society of Mechanical Engineers, New York (1998)
20. Lie, S.T., Yang, Z.M., Gho, W.M.: Validation of BS7910:2005 failure assessment diagram for cracked square hollow section T-, Y- and K-joints. Int. J. Press. Vessels Pip. **86**, 335–344 (2009)

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.