Crack Growth Simulation in Corrugated Plate Using XFEM

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Abstract- **Corrugated plates play an important role in many modern constructions applications. Being the main components like piles or stiffeners means they quite often subjected to high levels of stresses. The presence of flaw or crack in the structure of loaded corrugated plate may lead to the situation of crack growth and then catastrophic failure. Extended Finite Element Method is used to avoid remeshing during crack growth simulation. In order to characterize crack growth in corrugated plate two methods were used which are virtual crack closure method and cohesive segments method. Two case studies were investigated in this study. In the first case the material behavior is assumed to be linear elastic, while in the second one the material behavior is assume to be elastic-plastic. The results obtained using the two methods showed a very good agreement both in linear elastic and elastic plastic cases.**

Index Terms— Crack Growth, Corrugated plates, CSM, VCCT, XFEM,

I. Introduction

The main idea behind introducing corrugated plates is to increase stiffness of thin plates without adding stiffeners. The corrugated plates used in buildings has a thickness ranging from 2 to 5 mm, while those being used in fabricating bridges girders may has a thickness of 8 to 12 mm. These mentioned thickness ranges would never succeed to withstand loading conditions in the building and constructions applications without being corrugated [1]. Being members of buildings, bridges or other structural applications, corrugated plate are usually subjected to dynamic loads of different natures that might result due to various reasons. The probability of presence of flaw, micro cracks, minute defects may lead to catastrophic failure far below the expected load. This catastrophic failure is attributed to the possibility of crack growing under loading especially dynamic load. The level of the stresses resulted at crack depend on the applied load and the shape factor (C) which incorporates the effects of geometry. Relation between crack length and stress intensity factor in corrugated plates for different crack orientation and loading conditions is studied by Laftah [2] using Extended Finite Elements (XFEM) in ABAQUS software. It is shown that the value of Stress Intensity Factor (SIF) and shape factor are generally increasing when crack length is increased under same loading condition. Moreover Laftah studied different crack locations (in the web and in the flange) with loading applied once in the direction of corrugation and then perpendicular to the corrugation direction of the plate.

When the value of SIF at crack tip in the first mode (KI) reaches certain value (KIc) which is known as critical stress intensity factor, then the crack is more likely will start to grow. There are number of methods may be used to simulate crack growth in literature [3] . In the present study the crack growth will be calculated using two methods, the first one is Virtual Crack Closure Technique (VCCT). This technique will be used in ABAQUS and is primarily based on the concept of strain energy release rate. VCCT determines energy-release rate, assuming the energy needed to separate a surface equals to the energy needed to close this surface [4]. The other method will be used in this study is Cohesive Segment method, where crack propagates by reaching critical value at which cohesive traction disappears [5]. Both of the VCCT and cohesive segment methods will be executed in ABAQUS and based on XFEM. The second method is using XFEM based on the Cohesive Segment Method (CSM). In this method the situation of crack propagation does not necessarily require the existence a dominant crack. The main idea about behind CSM is that during crack propagation the separation process is constricted to planes in 3D domain and to line segment in 2D domain [6].

The aim behind this work is to study crack growth in carbon steel corrugated plate using two methods VCCT and CSM, and to compare the results of these two methods assuming the material once linear elastic and other time elasto-plastic.

II. Methods and procedures Properties and Geometry of Corrugated Plate

Corrugated plate used in the study is carbon steel with material properties are given in Table (1) below [7].

Table (1) Mechanical properties of corrugated plate under study.

Young's Modulus	Poisons Ratio	Critical Energy Release Rate
E=200 GPa	0.3	G_{IC} = 18 KN/m

The dimensions and geometry of the used plate is shown in fig.1 and table (2) below.

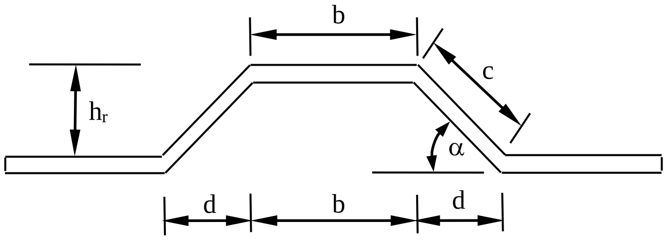


Fig. (1) Corrugated plate geometry [8]

Table (2) Dimensions the corrugated plate under study [8]

Symbol	b	c	d	h_r	□
Dimension (mm)	147	147	104	104	45°

Extended Finite Element (XFEM) Approximation

For the current linear elastic fracture mechanics case, let Ω∈R^dbe continuous domain of d dimensions and Γ_c∈R^d is 2-D crack surface. The extended finite element approximation is given by [10]

$$u(x) = \underbrace{\sum_{i\in k} N_i(x)\,u_i}_{\text{Classical}} + \underbrace{\sum_{i\in k^*} N_i^*(x)\,a_i}_{\text{Discontinuous Enrichment}} + \underbrace{\sum_{i\in k^{**}} N_i^{**}(x)\,b_i}_{\text{Tip Enrichment}} \quad (1)$$

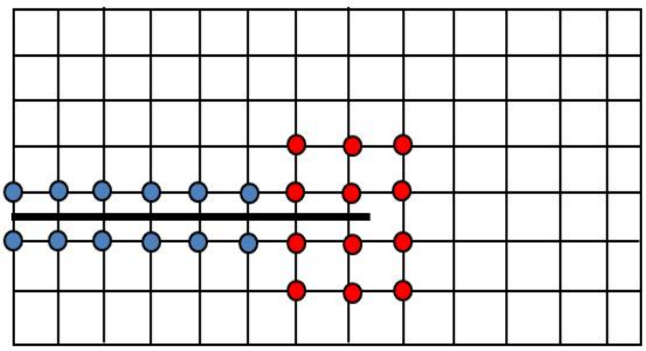


Fig. (2) Definition of the node sets K^* and K^{**}. The nodes in K^* are represented by blue circles and the nodes in K^{**} are represented by red circles

Where u(x) is the total displacement, Ni is classical finite element shape function, N* is discontinuous enrichment shape function, N** is crack tip enrichment shape function, ai is displacement due to discontinuous displacement, and bi is displacement due to the crack tip enrichment. K, K*, and K** are nodes sets.

The first term is a classical FEM approximation with shape functions Ni(x) and nodal variables ui. The second term is an enrichment function that takes the discontinuity in the displacement across crack surface into account. The third term or function is an enrichment that accounts for the singular stress strain at crack tip. These two enrichment functions are calculated at nods K* and K** respectively, see figure (2). Additional degrees of freedom are introduced to these nodes namely ai and bi.

III. Crack Growth Simulation

The process of crack growth consists of three stages namely crack initiation, crack propagation and finally failure. The crack growth with all the three stages is simulated using extended finite element method where there is no need for re-meshing. One of the most important criteria that characterize crack growth situation is the max principal stress [9] as indicated in equation (2). According to this criterion the damage is initiated when maximum principle stress max exceeds max allowable stress

$$\left\{\frac{\langle\sigma_{\max}\rangle}{\sigma^{o}_{\max}}\right\} \geq 1 \quad (2)$$

Fig. (2) Definition of the node sets K^* and K^{**}. The nodes in K^* are represented by blue circles and the nodes in K^{**} are represented by red circles

The Ma compression does not initiate crack. Crack growth in corrugated plate is studied by presenting central crack in the flange. The simulation of crack growth is carried out using VCCT method and CSM. Each of the two methods is implemented twice by considering linear elastic material first and then by considering the effect of elsto-plasticity. Loading conditions and crack locations in the corrugated plate are presented in figure (3).

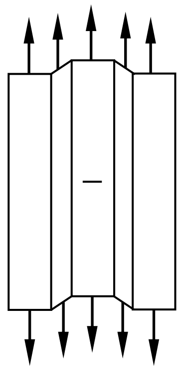


Fig. (3): Crack locations and load condition

IV. Virtual Crack Closure Technique Extended Finite Element Method:

The VCCT will be used in ABAQUS environment along with the XFEM to compute the strain energy release that characterizes the onset of crack growth. The mixed mode equation for VCCT based on strain energy release used by ABAQUS is given as follows[3]:

$$\frac{G_{eq}}{G_{eqC}} = \left(\frac{G_I}{G_{IC}}\right)^{am} + \left(\frac{G_{II}}{G_{IIC}}\right)^{an} + \left(\frac{G_I}{G_{IC}}\right)^{ao} \quad (3)$$

Where GI to GIII are energy release rates for first second and third modes of deformation, GIC, to GIIIC are critical energies of the three modes and am, an, and ao are empirical constants and for the present study their value is equal to 1.

The geometry and loading condition employed in this study relies within the first mode. Crack will tend to propagate when Geq the equivalent strain energy release rate becomes greater than GeqC the critical strain energy rate at the tip of the crack. Calculations showed that the value of GeqC for the corrugated plate used in this study is 18 KN/m as indicated in Table (1).

V. COHESIVE SEGMENTS METHOD BASED ON EXTENDED FINITE ELEMENT METHOD:

In this method XFEM will be used in ABAQUS environment in order to simulate the spread and growth of central crack in the flange of the corrugated plate. The crack is propagating at arbitrary path based on the level of energy released in that path. The 2D elastic behavior is represented by the following relation [2].

$$t = \begin{Bmatrix} t_n \\ t_s \end{Bmatrix} = \begin{bmatrix} k_{nn} & 0 \\ 0 & k_{ss} \end{bmatrix} \begin{Bmatrix} \delta_n \\ \delta_s \end{Bmatrix} = K\delta \quad (4)$$

Where t is stress, t_n the peak normal stress and □$_n$ is normal deformation in case of pure normal deformation while t_s, shear stress, and □$_s$ are shear stress and shear deformation in case of pure shear deformation. The initial and final values of stresses and deformations are represented t_n^o, t_n^f, t_s^o, and t_s^f, and initial and final values of the ormations are represented by δ_n^o, δt_n^f, δ_s^o and δ_s^f.

Degradation and failure of the elements being enriched is characterized by damage modeling where the failure is divided into two parts which are initiation and evolution of the damage. The damage is considered to start or initiated linearly, but one it starts then damage may evolve as per user defined law.

Fig. (4) Presents a possible type of linear damage and separation mechanism.

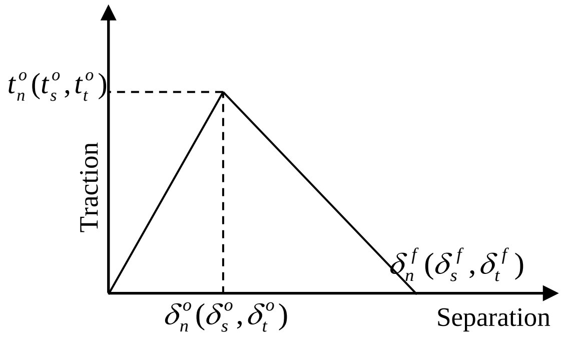


Fig. (4): Linear damage and separation Law

VI. Results

Linear Elastic Crack Growth:

In the present case a crack (2a length) is introduced in the flange of the corrugated plate, as indicated in figure (2). The plate is loaded axially and perpendicular to the corrugation direction. Crack growth is simulated using VCCT and CSM in XFEM using ABAQUS. Curves in figure (5) indicate that the behavior of the material is completely linear throughout all the phases of crack growth until fracture point which represents the maximum applied load.

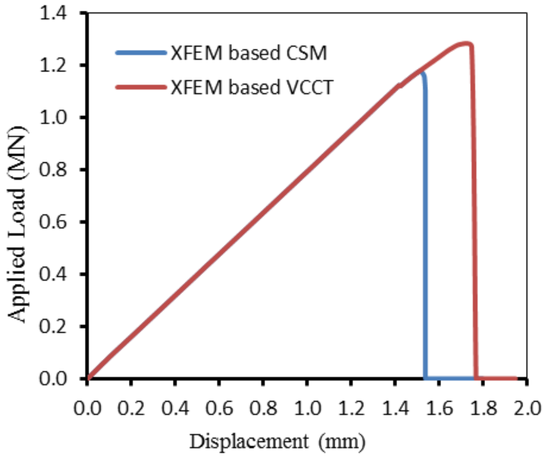
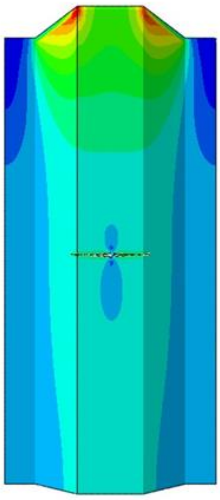
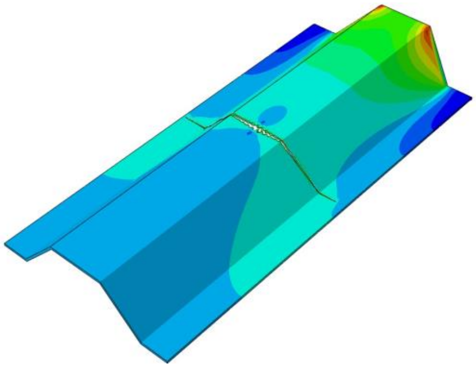


Fig. (5) Load displacement curve for linear elastic material



a. Crack at time step 0.8



b. Crack at time step 1.0

Fig. (6) Central crack growth at two instants (CSM) method

Pictures presented in figure (6) visualize how the crack is propagated during simulation in two different instants. It is obvious that crack is spreaded evenly despite the geometry of the corrugation.

VII. Elasto-Plastic Crack Growth:

A.EXPERIMENTAL WORK

In this case the crack is assumed to propagate in an elasto-plastic material. The condition of elasto-plastic occurs after the material passes the yield point and continues until failure. Figure (7) shows the stress strain curve for a specimen prepared from a corrugated plate with same material properties adopted in this study. The relation between true stress and plastic strain in elasto-plastic zone is given in table (3) which is obtained from the experimental tensile test.

Table (3) True stress strain curve

True Stress (MPa)	Plastic Strain
374.71	0.0000
374.52	0.0047
374.17	0.0049
374.08	0.0050
375.49	0.0075
375.31	0.0077
384.03	0.0136
384.25	0.0137
385.39	0.0143
385.54	0.0144
385.66	0.0145
389.41	0.0159
476.72	0.0442
477.90	0.0446
478.14	0.0447
479.29	0.0452
496.88	0.0525
497.49	0.0528
523.73	0.0654
524.08	0.0656
524.95	0.0660
525.11	0.0661
532.12	0.0700
533.21	0.0706
636.13	0.1695
637.93	0.1731
638.04	0.17
639.23	0.18
639.17	0.18

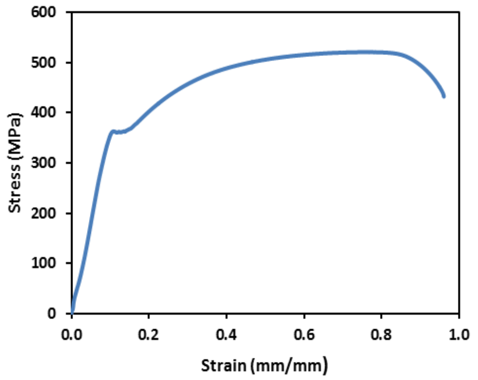


Fig. (7) Experimental stress-strain curve

The load displacement for this case is shown in figure (8) for both the VCCT and CSM based on XFEM. The two curves in the figure are identical in describing the growth of the crack. Moreover the curves indicate that the behavior is completely nonlinear starting from crack initiation until fracture point.

Figure (9) shows the crack growth of the corrugated plate at the end of simulation, the figure also give an indication about stress distribution around the crack and all over the plate.

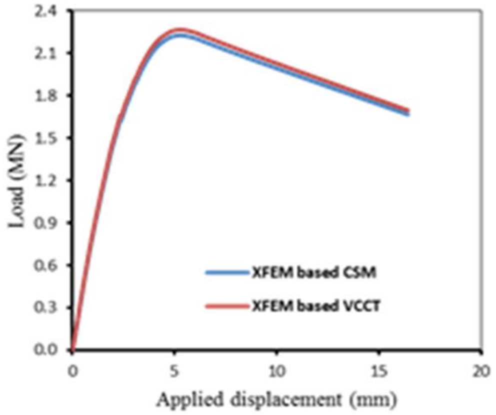


Fig. (8) Load displacement curve for elasto -plastic material

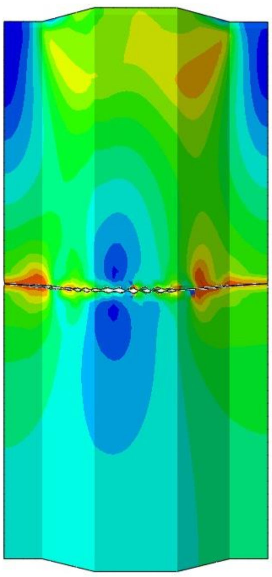


Fig. (9) Crack at the end of simulation (VCCT)

VIII. Conclusion

Based on XFEM crack growth in corrugated plates characterized using VCCT and CSM methods. Two case studies are considered in this study. In the first the martial behavior is considered to be linear elastic where Simulation showed good agreement between the results obtained by the two methods. The only deviation that might be noted is that the value of the load required for failure in the VCCT method was greater. The reason could be attributed to the fact that the damage in VCCT occurs as a result of the ratio between the energy release rate and the critical energy, while in CSM the damage occurs according to linear law relates initial and final values of stresses and strains.

In the second case study (elasto-plastic) there was a good agreement between load-displacement curves obtained by the two methods. The reason is that in this case the behavior of the material was nonlinear and true stress strain curve is used to describe material behavior. The results of this study showed how crack my propagate in corrugated plate under tensile loading where the first mode of deformation is dominant.

IX. References

[1] F. M El-Amin; M.F. Abdel-Khalek; M. M. Ahmed and S. R. Gad, "Nonlinear Behavior of Cantilever girders with Corrugated Steel Webs", Journal of Engineering Sciences, Assiut University, Vol. 36, No. 6, pp.1319-1338 November 2008.

[2] Laftah, Rafil Mahmood, “Study of Stress Intensity Factor in Corrugated Plate Using Extended Finite Element Method”,Eng. & Tech. Journal, Vol. 34, Part(A), No. 15, 2016.

[3] Kamal Keswani1, Krishna Lok Singh & A. Arokkiaswamy; Computation of SIF and Crack Growth Simulation using XFEM Techniques, Conference on Advanced Research in Mechanical Engineering (ICARME-2012), 13th May, 2012.

[4] Joshua H. Melson; Fatigue Crack Growth Analysis with Finite Element Methods and a Monte Carlo Simulation, M.Sc. Thesis, Virginia Polytechnic Institute and State University, 2014.

[5] E. Barbieri and M. Meo; A Meshless Cohesive Segments Method For Crack Initiation and Propagation in Composits, 17th International Conference on Composite Materials, 27-31July 2009, Edinburgh, UK.

[6] J. J. C. Remmers, R. de Borst, A. Needleman, “A cohesive segments method for the simulation of crack growth”, Journal of Computational Mechanics, Vol.31, No.1, pp. 69-77 Springer-Verlag 2003.

[7] Marc Meyers and Krishan Chawla, “Mechanical Behavior of Materials”, Second Edition, Cambridge University Press, 2009.

[8] Richard S., Hassam H.,Wagdy G., Robert G., Mohamed E., "Corrugated Web Girder Shape and Strength Criteria", National Center for Engineering Research on Advance Technology for Large Structural Systems,ATLSS Report No. 03-18, Civil and Environmental Engineerun, Lehigh University, 2003.

[9] T.L. Anderson, “Fracture Mechanics, Fundamental and Applications”, Third Edition, CRC Press, Taylor and Francis Group, 2005.

[10] Belytschko, T., Black, T., "Elastic crack growth in finite elements with minimal remeshing.", (International Journal for Numerical Methods in Engineering", 45(5):601– 620, 1999).