Journal of Theoretical and Applied Mechanics, Sofia, Vol. 48 No. 1 (2018) pp. 69-75
SOLID MECHANICS

# DETERMINATION OF THE CRACK RESISTANCE PARAMETERS AT EQUIPMENT NOZZLE ZONES UNDER THE SEISMIC LOADS VIA FINITE ELEMENT METHOD

VLADYSLAV KYRYCHOK*, VASYL TOROP
*The E.O. Paton Electric Welding Institute of the National Academy of Sciences of Ukraine, Kyiv, Ukraine*

[Received 16 October 2017. Accepted 12 March 2018]

ABSTRACT: The present paper is devoted to the problem of the assessment of probable crack growth at pressure vessel nozzles zone under the cyclic seismic loads. The approaches to creating distributed pipeline systems, connected to equipment are being proposed. The possibility of using in common different finite element program packages for accurate estimation of the strength of bonded pipelines and pressure vessels systems is shown and justified. The authors propose checking the danger of defects in nozzle domain, evaluate the residual life of the system, basing on the developed approach.

KEY WORDS: Seismic analysis, crack growth, nozzle, vessel, distributed pipelines, response spectrum.

## 1. INTRODUCTION

Nowadays, the problem of the evaluation of residual resource of pressure vessels with defects is not fully solved. This procedure is performed in order to know, how much time the equipment can be exploited, without repairing or changing the parts. For qualitative estimation in common situation, it is important to know the geometry of the part with real or postulate defect locations, the material and its properties, the history and parameters of loads, postulate loads, which characterize abnormal situations during exploitation.

The present paper is devoted to postulate crack behaviour under the seismic loads in heatexchanger, the part of nuclear power plant (NPP). In common situations, according to [1], this procedure is not mandatory in project. But in practice, as mentioned in [2] and [3], fatigue and corrosion can initiate macro cracks in pipelines and equipment, most of all in welded joints zones. Exploit organization must know, if these objects are safe, or if it is necessary to change regimes, repair defects, make diagnostic more often, etc. Some consideration of this problem can be noticed in standard for pipelines [4]. Absence of material constants and necessity of experimental research are the disadvantages of this methodology.

---

*Corresponding author e-mail: k0965976337@gmail.com

Guideline “VERLIFE” [5] was created by international society for NPP with reactor WWER-1000. It includes recommendations for strength estimation of tubes, equipment and support elements. The recent version of the guideline suggests using specific conservative constants of some material for defect growth rate evaluation. It also allows us partially to take into consideration temperature regime, thermal and radiation embrittlement. This feature is especially important for assessment of vessels, which work over the project period. Taking into account the optional character of guideline “VERLIFE”, Ukrainian engineers have some problems with the estimation of fatigue and corrosion crack growth. When such cracks arise, every organization solves this problem individually and uses its own analytical methods to forecast the residual system resource. In our opinion, the most qualitative methodology is proposed by American standard [6], which gives conservative crack resistance properties for most of steels, used at NPP, depending on operation temperature, environment and other parameters.

## 2. APPROACHES TO ASSESSMENT OF SEISMIC LOADS IN PRESSURE VESSELS

In common situations, two approaches for seismic analysis of constructions are popular. They are response spectrum method and dependent on time dynamic analysis method. The first approach, based on response acceleration of supports, depends on resonance oscillation. To implement the method, it is necessary to perform modal analysis and then, apply the response acceleration to the support elements at resonance frequencies.

Assuming, that the seismic reactions in common event are periodic and not sinusoidal, we know this load is the sum of harmonic functions (Fourier range). That is why, the supports can assume the full spectrum of response accelerations. This hypothesis induces us to determine the response loads conservatively, as the sum of all forces under each resonance frequency. Guideline [8] suggests getting conditional resulting value, as square root of the sum of squares (SRSS) of all response loads. Taking this into account, it can be noticed, that the larger frequency range is, the larger reaction forces and stresses are. In practice, the range 0.5-30 Hz is taken into consideration, others are neglected. Response spectrum method is used only for linear systems. If the model has non proportional dependencies (different stiffness in different directions, gaps, dissipative nodes etc.), these parts are tried to linearize. In this case, the solving accuracy is losing.

The dependent on the time dynamic analysis method is based on dynamic equations and seismic accelerogram, defined at peak ground acceleration. This approach is suitable for solving nonlinear systems, but it is more sophisticated and much more expensive than the response spectrum method. In fact, most manufactory objects offer only response spectrum acceleration as output data for modelling. If the floor accelerogram in such case is needed, it is possible to get it conservatively, performing the dynamic analysis of structure and taking for boundary conditions the accelerogram “CA-482” at zero mark. The analytical form of “CA-482” can be found in [8].

According to [9], nozzle zones and support elements are the parts, which can be destructed during earthquake. The main cause of equipment branch connection domains disruption are reaction forces of joined pipelines.

The seismic resistance assessment procedure for standard parts is simplified. It induces us to evaluate only general bending and general or local membrane stresses. Using these criteria, it is enough to operate only with beam model. Usually, in order to receive general stresses at nozzle domain, it is accepted to make two steps. The first one is the studying of joined pipelines in suitable codes to determine the reaction forces and moments at nozzle. In this stage, it is possible to use the most popular distributed piping solving program “Intergraph Caezar II” (in eastern Europe such codes are popular, as DPIPE, ASTRA-AES and others). The second analysis is based on studying the equipment via finite element method with more universal programs (Ansys, Abaqus, Nastran etc.), using the output reaction forces and moments from the first step.

The very important factor when getting the seismic stresses is the load orientation. We need to take it into account, because the direction of response forces and moments change during the period of time. If we get the seismic stresses, all the components of tensor by using the SRSS rule are positive. If we consider the combination of seismic and static regimes, we know exactly the direction of the last, because it does not change during the time period. In this occasion, to get conservative stress values of summary condition, the directions of seismic and static components should be the same. If we need to evaluate the crack parameters, using the mentioned before two-stepped modelling is not correct. This way is wrong, because during this simulation compressive stresses in some elements arise. Determination of stress intensity factor (SIF) is allowed only under tension loads. If we apply the forces and moments to the 3D model of nozzle, at the first domain tension stress will arise, at the second – compressive one. But this condition is only one of the probable situations. If the crack is situated in compressive zone, conservative evaluation of SIF is impossible. The second problem of the two-stepped modelling is the presence of general and local stresses. They can have different directions and this condition will not allow to determine maximum tension across the full crack front. To avoid all those mentioned aspects, it is necessary to study joining pipelines and pressure vessel together in conjunction.

## 3. COMPUTATIONAL MODEL

The object of the investigation was to determine the probability of a leak appearance in the defected zone of the heatexchanger after the earthquake. For this aim, it was created the model of the equipment and joining tubes between the vessel and the fully fixed supporters. To simplify the sophisticated pipelines modelling, it was written the Python code for import the objects from DPIPE into Abaqus/CAE. The main algorithm is based on translating the information from solving DPIPE file (node coordinates of tubes, boundary conditions, load parameter, material properties, section characteristics) to the Python script, readable in Abaqus. To decrease the solving time, the straight piping cells are modelled as Beam elements (the mesh consists from linear line elements of type PIPE31). To consider the ovalization stiffness reduction of elbows, they are created as Solid parts (the mesh consists from linear hexahedral elements of type C3D8R). The fragment of the geometry model is represented on Fig. 1.

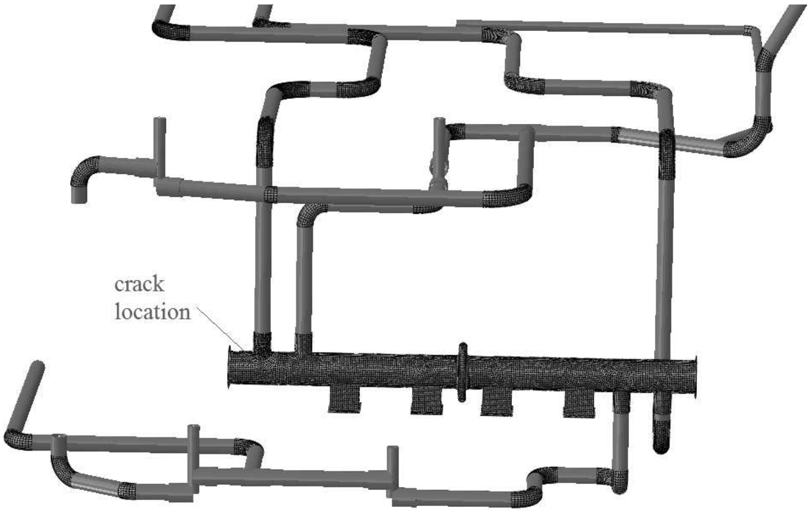

Fig. 1. Fragment of modelled heatexchanger and joining pipelines.

The body of the vessel is made from tube 325 × 12 mm, the nozzles from pipe 168 × 9 mm. The operation pressure is 2.4 MPa. The temperature of the environment is 150°C. The material of the heatexchanger and joining parts is 08H18N10T. Young's modulus is 194 GPa. Density is 7900 kg/m$^3$. One of the supports of heatexchanger is fully fixed, the others work as sliding guide in order to avoid the exceeding of temperature stresses. Modal analysis was executed on the range of 0.5–30 Hz. The response spectrum accelerations and damping were taken according to [1].

If the container is made from stainless steel, the most widespread crack initiation cause is intergranular corrosion at the interior side of the wall near the welded joint. At the same time, we postulated the defect in domain, where the maximum seismic stress arises (see Fig. 2). The crack was semielliptical with 12 mm length and 9 mm depth. To create the optimal finite element mesh, the defect zone is modelled as a detached cell, meshed via quadratic tetrahedral elements of type C3D10 and linear wedge element of type C3D6, bonded with the shell of the main vessel part via tee constraint (the mesh of main part consists from linear quadrilateral element of type S4R). The fully created object consists from 49138 elements. The determination of the all needed model parameters is based on Linear Elastic Fracture Mechanics.

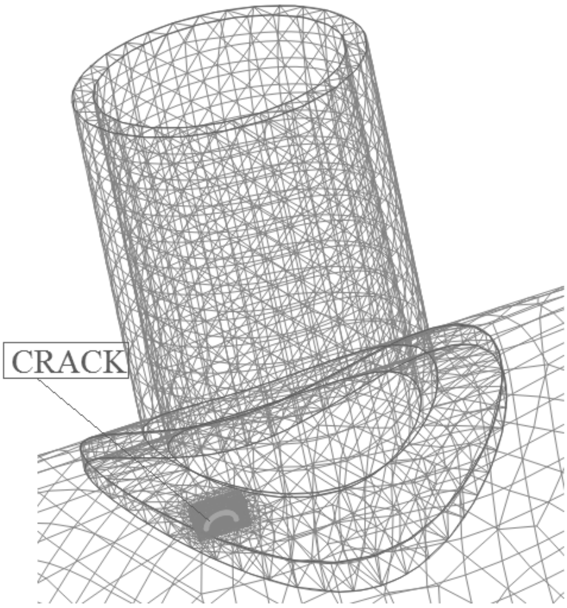

Fig. 2. Location and shape of the crack.

The proposed approach allows to estimate static and dynamic loads of each element with minimal operational memory and Central Processing Unit requirements. The solution time of such and similar models is about several minutes.

## 4. RESULTS AND ANALYSIS

In Fig. 3, the normal stresses across the crack front in cut section of defects domain are represented. The maximum normal stresses and SIF $K_I$ were determined as the algebraic sum of static (the own weight + pressure + temperature) and obtained from response spectrum analysis dynamic component.

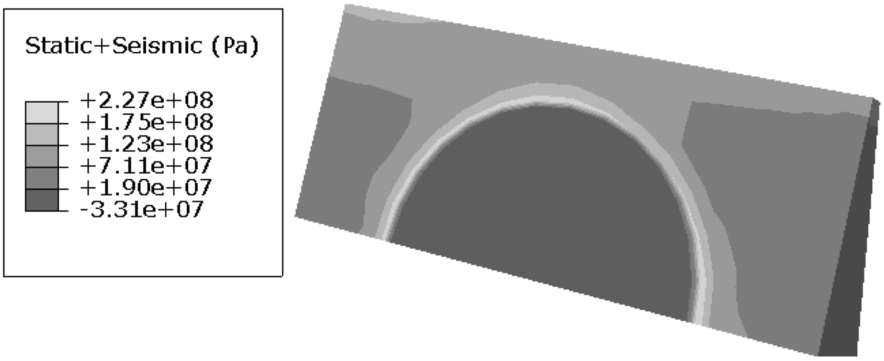

Fig. 3. Distribution of maximum stresses across crack shape under the simultaneously acted static and seismic loads.

Basing on the stress field on surface of crack front, it is possible to get SIF by formula (1):

$$K_I = \sigma \sqrt{2\pi r} \,, \tag{1}$$

where $\sigma$ is the normal stress at point of crack tip domain, acting across defect shape, r is the shortest distance between crack front and this point.

We have calculated, that the maximum SIF is 8 MPa $\mathrm{m}^{1/2}$. It is more than threshold stress intensity factor of the stainless steel (according to [6] $K_{Ith} \approx 5.5\,\mathrm{MPa\,m}^{1/2}$ at 150°C). The crack growth after the earthquake can be found from Paris equation (2). Our task was solved for zero-based stress cycle. It was taken in account, because seismic normal tension stresses exceed static components at crack tip and $\Delta K_I$ can change from 0 to maximum SIF during the period

$$\frac{da}{dN} = C\,(\Delta K_I)^n \,, \tag{2}$$

where $da/dN$ is crack elongation per cycle, $C$ and $n$ are material constants, $\Delta K_I$ is SIF range.

Methodology [10] suggests considering 50 seismic cycles by determination the fatigue damage of material. For the regions with high probability of earthquake, this value ought to be increased. The calculation of crack growth was performed, using material constants $C = 2.38 \times 10^{-9}$ ($C$ produces fatigue crack grow rates in the units of mm/cycle when $\Delta K_I$ is in the units of MPa $\mathrm{m}^{1/2}$) and $n = 3.3$, according to [6] with taking into account the operating temperature. The computation shows that the maximum defect increasing by using such parameters is $0.11$ $\mu$m. We can be sure, this value is very small and safe for present equipment.

## 5. CONCLUSIONS

The review of standard methods for estimation of fatigue crack growth parameter is represented. The approaches to seismic assessment of important equipment with defects, using conservative material constants, are analysed. The principles of pressure vessels with joining pipelines modelling are proposed. Basing on the example of NPP heatexchanger, the opportunity of macro defect condition assessment in domain of stress localization at the equipment after the earthquake is shown. The present approach can be suitable for damage estimation of equipment with large wall thickness, containers manufactured from material with low fracture toughness, and vessels at objects situated in seismic active regions.

## REFERENCES

[1] Rules and Regulations in Nuclear Power Engineering. Regulations for Strength. Analysis in Nuclear Power Plant Equipment and Piping. PNAE G–7–002–86, M., Energoatomizdat, 1989, 525 p. (In Russian).

[2] TOROP, V. M. The Pipelines, Containers and Pressure Vessels Limit Assessment, Based on Developed Expert System, Dissertation of the Doctor of Technical Science, 05.02.09 / NAS of Ukraine, – K., 2006. – 360 p. (in Ukrainian).

[3] DUB, A. V., V. A. DURYNIN, ET.AL. Development Ultrasonic Testing Procedures and Determination of Performance of the Assembly of the Joints of Header to Steam Generator PGV-1000M, Technical Diagnostics and Non-destructive Control, No. **4**, 2014, 36-51 (in Russian).

[4] DSTU-N B V.2.3-21:2008. Assessment of the Residual Strength of Magistral Pipelines with Defects (In Ukrainian).

[5] Guidelines for Integrity and Lifetime Assessment of Components and Piping in WWER Nuclear Power Plants (VERLIFE), 2013.

[6] ASME Boiler and Pressure Vessel Code, Section XI: Rules for In-service Inspection of Nuclear Power Plant Components.

[7] Abaqus Scripting Reference Manual. – USA, Providence, RI., 2010, – 2825 p.

[8] RTM 108.220.37-81 Strength Calculation under the Seismic Load (In Russian).

[9] Seismic Resistance Analysis Technique of the Active NPP Elements via Seismic Margin Assessment Method, MT-T.0.03.326-13 (In Russian).

[10] Technical Condition Assessment Technique, Basing on Strength Parameters and Analytical justifying of Pump Bodies Resource Remapping at Ukrainian NPP. MT-T.0.08.158-05 (In Russian).