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Destruction of high pressure vessels in pipeline structures

Uszkodzenia zbiorników wysokociśnieniowych w konstrukcjach rurociągów

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ABSTRACT: The article indicates that engineering design criteria do not provide measures to prevent failures; this is evidenced by the occurrence of many accidents. Fracture prevention criteria should be derived from the principles of fracture mechanics, what should be developed further. However, the current concepts of fracture mechanics, when properly applied, provide an opportunity to ensure the reliability of the structure or organise the supervision of expensive structures to ensure their safe operation. These methods of preventing damage can be divided into two large groups: 1) checking for the formation of cracks and 2) monitoring their development. Both methods are based on similar principles; it would be easier to explain them with examples. To ensure the safe operation of the pressure vessel used in the reactor, the maximum allowable initial crack size should be known. The size of this crack should not expand to a critical point during the entire operation of the reactor. Knowing how the process of crack propagation proceeds and how the structure behaves during failure, it is possible to calculate the critical size of the defect and, based on this, calculate the maximum allowable size of the crack at the beginning of operation. Proper inspection of the new vessel will eliminate the possibility of shells that are larger than the original size. Checking for the presence of cracks, and determining their rate of growth during operation, presents significant difficulties. Therefore, checks should be avoided during operation. If the fracture and crack growth calculations, as well as the initial checks, are carried out correctly, then checks made during operation are an optional extra. However, in practice, such checks should still be performed. For vessels used in reactors, remote observation of crack growth using ultrasonic waves is a particularly useful method. If a crack is found, measures must be taken to either repair or replace the partially destroyed element.

Key words: fracture and crack growth, operation, high pressure, crack retardation, stresses, design, fracture mechanics.

STRESZCZENIE: W artykule wskazano, że kryteria na etapie tworzenia projektu technicznego często nie uwzględniają środków zapobiegających awariom, o czym świadczą liczne wypadki przy pracy. Kryteria zapobiegania powstawaniu pęknięć powinny być wyprowadzane z zasad mechaniki powstawania pęknięć, co wymaga dalszego rozwoju. Jednak obecne koncepcje mechaniki powstawania pęknięć, przy ich właściwym stosowaniu, dają możliwość zapewnienia niezawodności konstrukcji lub zorganizowania nadzoru nad kosztownymi konstrukcjami, aby zapewnić ich bezpieczną eksploatację. Te metody zapobiegania uszkodzeniom można podzielić na dwie duże grupy: 1) kontrola pod kątem powstawania pęknięć, 2) monitorowanie ich wzrostu. Obie metody opierają się na podobnych zasadach i lepiej wyjaśnić je na przykładach. W celu zapewnienia bezpiecznej eksploatacji zbiornika ciśnieniowego używanego w reaktorze należy znać maksymalną dopuszczalną początkową wielkość pęknięcia. Wielkość takiego pęknięcia nie powinna wzrosnąć do wartości krytycznej przez cały czas pracy reaktora. Wiedząc, jak przebiega proces propagacji pęknięć i jak zachowuje się konstrukcja podczas uszkodzenia, można obliczyć krytyczną wielkość uszkodzenia i na tej podstawie obliczyć maksymalną dopuszczalną wielkość pęknięcia na początku eksploatacji. Prawidłowa kontrola nowego zbiornika wyeliminuje możliwość wystąpienia pęknięć większych niż o pierwotnym rozmiarze. Kontrole pod kątem obecności pęknięć i określenie tempa ich wzrostu podczas pracy wiążą się z dużymi trudnościami. Dlatego należy unikać wykonywania kontroli podczas pracy. Jeżeli obliczenia dotyczące pęknięć i ich wzrostu, jak również kontrole wstępne, zostały przeprowadzone prawidłowo, to kontrole podczas eksploatacji byłyby opcjonalnym dodatkiem. Jednak w praktyce takie kontrole i tak są przeprowadzane. W przypadku zbiorników używanych w reaktorach szczególnie przydatną metodą jest zdalna obserwacja wzrostu pęknięć za pomocą fal ultradźwiękowych. W przypadku stwierdzenia pęknięcia należy podjąć działania w celu naprawy lub wymiany częściowo zniszczonego elementu.

Słowa kluczowe: pęknięcia wraz z ich propagacją, eksploatacja, wysokie ciśnienie, opóźnianie rozwoju pęknięć, naprężenia, projekt, mechanika powstawania pęknięć.

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Introduction

An important aspect of improving the reliability of a structure is to increase the probability of detecting a crack before it reaches a critical size. Large cracks are easier to detect than small ones. Therefore, it is preferable to use materials in which the critical crack dimensions are large. The crack resistance of the material should be evaluated in connection with the current stress level (Kerimov and Mamedzade, 1976, 1977).

Comparison of materials in terms of their crack resistance should be based on the assumption that the structural performance of the materials is of the same order: it is assumed that the design of the structure has been optimised so that each material operates at the same ratio of working load to yield strength, so that the working load $\sigma = \alpha\sigma_{ys}$, where $0 < \alpha \leq 1$, is the same for all considered materials.

Task setup

An even more important characteristic of a material than its crack resistance is the crack propagation time. The total propagation time is almost independent of the critical crack size, since the growth of the crack at the last stage of its propagation is extremely fast.

Large structures, whose destruction would lead to certain economic damage and, most likely, to the loss of many human lives, must be reliable. Examples of such structures are ships, aircraft, bridges, pipelines, storage tanks, pressure vessels (in nuclear reactors) and rocket engines. Despite the fact that damage occurrence is relatively small compared to the number of active structures, its absolute incidence rate is too large. The destruction of even one aircraft or reactor under operating conditions is already a great misfortune.

Classical engineering design criteria do not provide failure prevention measures; this is evidenced by the sad occurrence of many accidents. Fracture prevention criteria should be derived from the principles of fracture mechanics. Of course, methods of fracture mechanics should be developed further. However, the current concepts of fracture mechanics, when properly applied, can ensure the reliability of a structure or organise the supervision of expensive structures for their safe operation.

Task solving

These destruction prevention methods can be divided into two main groups: 1) checking for the formation of cracks and 2) monitoring their development. Both methods are based on similar principles. Let us explain them with examples.

To ensure the safe operation of the pressure vessel used in the reactor, the acceptable initial maximum crack size should be known. The size of this crack should not expand to a critical point during the entire operation of the reactor. Knowing how the process of crack propagation proceeds and how the structure behaves during failure, it is possible to calculate the critical size of the defect and, based on this, calculate the acceptable initial maximum crack size at the beginning of operation. Proper inspection of a new container will eliminate the possibility of cracks that are larger than the original dimensions. Checking for the presence of cracks and determining the rate of their growth during operation present significant difficulties. Therefore, checks should be avoided during operation. If the fracture and crack growth calculations, as well as the initial checks, are carried out absolutely correctly, then checks during operation would be redundant. However, in practice, such checks may still be performed. For vessels used in reactors, the remote observation of crack growth using ultrasonic waves is a particularly useful method. An example of crack propagation control is aircraft monitoring. During the lifetime of this structure, it is expected that cracks will grow. The critical sizes of cracks are calculated, and its propagation duration is determined from the minimum crack size from which it is possible to detect. Based on these data, an inspection period is selected so that until the crack size increases to a critical value, it can be detected several times. If a crack is found, measures must be taken to either repair or replace the partially destroyed element.

Basic concepts of fracture mechanics, the ability to design reliable structures

When presenting steel material, the shortcomings and limitations of these concepts were show. When using these concepts in the design of large structures or their components, additional difficulties are encountered. Some of them only concern constructions of a certain type, while others are more general. The article deals with particular issues that arise when monitoring the destruction of high-pressure containers. However, some of the information presented here has a wider application. The selection of material to prevent fracture is also considered. In the final part, the questions of applying fracture mechanics to a special class of structures, namely, to the class of structures built from thin sheets reinforced with stiffeners, are investigated.

For steel structures in general, and for pressure vessels in particular, fracture criteria are applied that differ from the fracture mechanics concepts outlined in this paper – to be specific, the Charpy test, the drop weight test, the crack retardation test, and the fracture analysis diagram. This is not the place to consider the usefulness of all these approaches. Furthermore, only those methods of fracture mechanics allowing a quantitative calculation of the structural strength, and only their application to extremely ductile materials will be considered.

A longitudinal crack may be developed in a thin-walled pressure vessel or pipeline. The stress acting across the crack is the circumferential stress $\sigma_H = pR/B$, where R is the radius of the vessel or pipe, B – wall thickness, p – internal pressure. For a through crack with a length of 2a, the stress intensity factor is expressed by the equation:

$$K_1 = M_F\,\sigma_H\sqrt{\pi\alpha} = \frac{pR}{B}\left[\left(1+1.61\frac{\alpha^2}{RB}\right)\pi\alpha\right]^{1/2} \quad (1)$$

Here M_F is the stress intensity increase factor which Folios theoretically obtained. The need for this coefficient is determined by the fact that the edges of the crack under the action of internal pressure bend outwards. According to Folios the magnification factor is

$$M_F = \sqrt{1+1.61\frac{\alpha^2}{RB}}$$

Several other (empirical) expressions have been proposed for the coefficient M_F. It is better to use the Folios result, at least because it is supported by the excellent program of testing pipes at various pressures carried out by Duffy, Iber, Maxey, McClure, and Kiefner (Broek, 1982). These investigators have tested various pipes of considerable length. Since low-strength samples were used in these tests (from steels with a yield strength ranging from 25 to 120 MPa), a correction of the expression for K for the plastic zone was applied in the form of an equation (2):

$$K_1 = M_F\,\sigma_H\sqrt{\pi\alpha\sin\left(\frac{\pi\sigma_H}{2\sigma_{ye}}\right)} \quad (2)$$

Fractures in pipes and thin-walled pressure vessels can occur by shearing, but the micro-separation mechanism can also be viscous depending on the temperature. In the latter case, from an engineering point of view, fractures are still brittle in nature: they are associated with small plastic deformations and occur at high speeds (Kerimov, 1970, 2009).

Crack areas in pipelines can extend for several miles, causing great damage unless conditions are met to stop the cracks. Fracture delay depends on the nature and compressibility of the substance transported through the pipeline. In the case where this substance is water or oil, there is a pressure drop due to leakage, the circumferential stress decreases.

As a result, the value of K may decrease, but this will happen only if the decrease in K due to the reduce in pressure occurs faster than its increase due to the size growth of the crack. If the transported medium is a gas, the degree of pressure reduction depends on the propagation velocity.

If, after the crack had propagated for some distance, its propagation velocity were reduced to zero, then the pressure in the pipe would be almost 30% of the initial level. If the crack growth rate is equal to the speed of sound in the gas, the decrease in pressure at the crack top is insignificant (Ragimova, 2013).

A crack in a pressure vessel is usually formed as a surface crack inside of the wall. It may be expected that in thin-walled vessels this cavity will grow at stresses lower than critical ones (due to fatigue processes or stress corrosion) until it develops into a through crack. After that, it is possible to detect this crack before its size becomes critical, as a leak appears in the vessels. Under more severe circumstances, a newly formed through cavity may already become critical. This shell will jump through the wall and, if the conditions on the wall are critical, will continue to propagate as a through crack. Otherwise, an instant shutdown may occur, followed by a leak (detectable) (Schuts, 1974).

Leakage to failure in thick-walled tanks is unlikely. Vessels with wall thicknesses on the order of 0.15 m used in reactors are not uncommon. The critical shell can be either an elliptical surface crack or an angular crack. Difficulties encountered in calculating the characteristics of the growth and destruction of such cracks are considered in some papers. In principle, surface cracks in pressure vessels can be treated in the same way as in any other design (Broek, 1982, Mammadzade et al., 2023).

The internal pressure in the vessel acts on the inner walls of the crack. The intensity of stresses arising under the action of this pressure should be added to the intensity arising under the action of normal stress (3):

$$K_1 = 1.1(\sigma + p)\sqrt{\frac{\pi\alpha}{Q}} \quad (3)$$

The second problem associated with thick-walled containers is the change in stress in the wall section. The greatest value is the stress in the inner part of the wall. Therefore, the stress intensity at the end of the main axis of the ellipse can be the largest (4):

$$K_1 = 1.1(\sigma + p)\sqrt{\frac{\pi\alpha^2}{Qc}} \quad (4)$$

This depends on the ratio of the stresses given by equations (3) and (4), as well as on the ratio α/c (it is assumed that the main axis of the shell is directed in the longitudinal direction, and the minor one – in the thickness direction).

Cracks and cavities usually occur in areas of stress concentration, such as at the edge of a hole. In a pressure vessel, a place prone to cracking is the channel connecting the pipe to the vessel. This area is usually reinforced to reduce stress concentration, and the welds are located outside the most dangerous area.

When analysing the process of crack propagation at the channel edge, the following difficulties are encountered:

- there is a large stress drop across the crack cross section;
- the crack is in the area of stress concentration;
- for the reasons indicated in paragraphs a and b, the stress intensity factor varies significantly along the crack front. It is unlikely that under these circumstances the crack will take the form of an ellipse or a circle;
- a complex system of stresses and an indefinite shape of the crack make it difficult to determine *K*;
- knowing the value of *K* and its change along the accepted crack front does not yet make it possible to determine the change in this front during subcritical crack growth (fatigue or stress corrosion). It is necessary to know the parameters of crack propagation in different directions.

There are several possibilities for solving this problem. For expensive reactor vessels, a broad research program is justified. Therefore, it seems reasonable to start with some particular test in which one well-defined place is simulated, for example, testing a flat plate for uniaxial or biaxial tension. The sample may have an initial cavity, which will grow during cyclic loading. Several tests of the same type can be stopped at different stages of crack propagation, after which the plate can be subjected to a breaking load. The resulting fracture surfaces will make it possible to determine how the shape of the crack changes (Kochanov, 1974).

A crack formed inside of a thin-walled pressure vessel by cycling or stress corrosion can grow and finally reach the outside of the wall. After that, a vessel leak is formed, which gives a real opportunity to detect this crack. However, there is also a possibility that the instability preceding the destruction will arise already in the presence of a surface crack. If the fracture is stopped after the crack has propagated through the wall, the vessel will leak and there is time to detect the crack before the "through" crack reaches critical size again. A vessel that ruptures in this manner satisfies the leak-to-rupture criterion (Rahimova and Mansurova, 2022).

Experimental part

Experimentally determined shell shapes can be used to establish stress intensity factors. In this case, finite element analysis can be applied. In view of the stress gradients acting across the crack, it is better to determine the stress intensity using the following technique (Gnilke, 1981). First, the stress field in the area with a crack is defined only in the place where there is no crack. When a crack cuts through this area, these stresses can no longer exist. In this case, the stress intensity factor can be determined by considering a crack with internal wedging forces, the distribution of which is equal to the distribution of internal discontinuous stresses in a given location, and using the superposition principle (Figure 1).

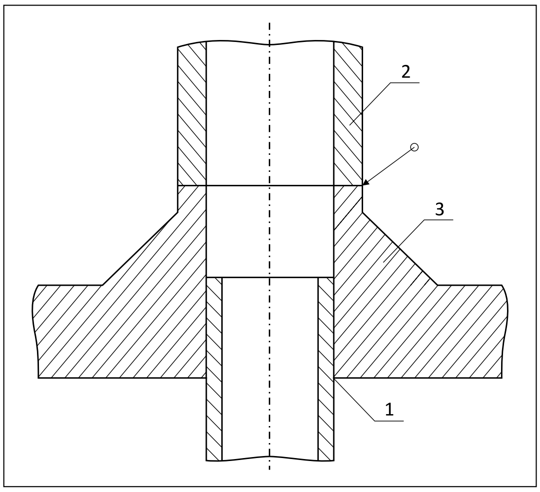

Figure 1. Crack on the edge of the channel; 1 – crack, 2 – pipe, 3 – vessel wall

Rysunek 1. Pęknięcie na krawędzi kanału; 1 – pęknięcie, 2 – rura, 3 – ściana zbiornika

This is based on the assumption that before a crack jumps through the wall, the corresponding surface cavity is semicircular in shape; this means that the through crack at the moment of slippage is equal in length to doubled wall thickness. It is assumed that the pre-failure instability in a size 2B crack occurs at a stress equal to the yield stress σ_{ys}.

Conclusion

Once the *K* value has been determined, the test results can be analysed further. The crack propagation process can be brought into line with the calculated value of *K*, as well as with data obtained from testing simple samples. As a result, *K* may decrease, but this will happen only if the decrease in *K* due to a reduce in pressure occurs faster than its increase due to the size growth of the crack. If the transported medium is a gas, the degree of pressure reduction depends on the crack propagation velocity and the speed of sound in this gas (decompression waves).

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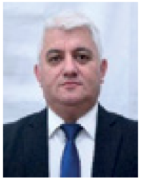

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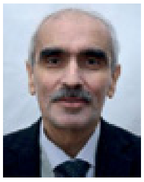

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