Influence of dynamic effects on the resistance of steel building structures to brittle failures

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Abstract

This paper deals with the results of experimental studies of the resistance to brittle failures in structural steels and elements. The characteristics of dynamic cracking resistance of structural steels are determined resulting from impact bend and brittle crack arrest tests. It is shown that under dynamic loading the transition to brittle failures at the stresses which are substantially lower than the yield strength of steel occurs at climatic negative temperatures. The case studies of local and total brittle failures of spherical and cylindrical gasholders were analysed using the obtained characteristics of steel dynamic cracking resistance.
Keywords: static, dynamic loading, cracking resistance, brittle failure, stress, tension, bending, brittle temperature, specimen, strength, structural steel.

1 Introduction

Brittle failures of steel structures occurring under the stresses that are significantly lower than design ones are generally attributed to low service temperatures and crack-like defects and, to a lesser extent, to dynamic effects. This consideration may be explained by the fact that an external dynamic effect on a structure is regarded as a random event that is unlikely to occur. However in view of the intensive construction of large storage capacity tanks used for oil products and liquefied gases, growth of the trunk gas pipeline network extending to large areas, a probability of external effects on structures becomes higher during a long structural service life.

Another important factor necessitating the consideration of dynamic factors is a structural and mechanical heterogeneity of welded joints. The occurrence of a brittle crack in the area of embrittled metal leads to the dynamic impulse that by

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its impact on a structural element is comparable to an external dynamic effect. In both cases the resistance to a brittle structural failure is determined by strength and strain characteristics of the material under dynamic loading. It should be noted that dynamic impact strength tests are widely used for evaluation of the resistance to a brittle failure in steels. According to the positive experience gained in structural steel service, the use of materials with guaranteed impact strength characteristics at low temperatures, undoubtedly, contributed to reduce structural failures caused by brittle failures. However the absence of a relationship between the impact strength characteristics, stress state, size and type of defects makes it impossible to predict residual structural service life in case structural steel elements have local damages resulting from their long service life.

2 Testing procedure

The design evaluation of the resistance to a brittle structural failure considering the stress state and size of defects is provided when using methods and criteria of fracture mechanics (Larionov [1]). Since there is an evident influence of low temperatures on characteristics of the resistance to the strain and structural steel failure, so in order to evaluate the resistance to brittle structural steel failures the methods based on the determination of critical brittle temperatures found a large application (Makhutov [2]).

To evaluate the influence of dynamic effects on the resistance to brittle failures experimental studies of the dynamic strength and cracking resistance of structural steels and structural elements were carried out. Considering the influence of the scale factor, stress state and type of loading critical brittle temperatures were also studied.

The characteristics of dynamic cracking resistance were determined by testing Charpy-type specimens with a fatigue crack and large-size specimens by means of a dropping weight. Internal dynamic effects were simulated by testing large-size flat specimens with the initiation of brittle cracks. The tests were conducted in a wide range of temperatures providing specimen failures in ductile and brittle states. The dynamic test data were compared with the corresponding data obtained for static loading.

The test specimens were manufactured from 20÷40 mm thick low-carbon structural rolled steels.

Charpy-type specimens with the cross-section of 10x10 mm and a fatigue crack having the depth $\alpha = 2.0 \div 2.5$ mm were tested by using a Guillery impact machine. The test results were recorded as “load-deflection” data presented on the oscillograms. The tests were carried out at the loading velocity of 5 m/s and in the temperature range 20–190ºC. The maximum loading value, absorbed energy and deflection were determined using the oscillograms. The crack depth was specified, and the portion of ductile component was determined by the fractured specimen surfaces. The failing stresses σ_{cd} and critical stress intensity coefficients K_{cd} were calculated using formulas for specimens with a crack subjected to transverse bending (Basko and Makhutov [3]).

The dynamic tests were carried out on large-size specimens using a vertical hammer with a dropping weight. The test data on "load-time" diagrams were recorded. The strain values resulting from the specimen loading were measured by means of a thermo-compensated bridge consisting of four active strain gauges with 10 mm gauge length which are directly glued on the test specimens. A cathode-ray oscillograph with a maximum sensitivity of 0.05 mV/mm and the pass band of up to 1 MHz was used as a recording instrument. Prior to dynamic loading each specimen was calibrated for static loading by the mass of the dropping weight. The value of maximum loading was determined by the oscillogram data. Then data obtained were used to determine the failing stresses σ_{cd} and critical stress intensity coefficients K_{cd}. The crack length was specified, and the portion of ductile component was determined by the fracture surface appearance.

For determination of the absorbed energy under dynamic loading a series of 3-4 test specimens was tested at the same temperature by varying the potential energy of the dropping weight. To evaluate the influence of dynamic effects on the resistance to the brittle failure similar specimens were tested under static loading. In the situation when a brittle crack formed in the areas of local metal embrittlement the resistance to the brittle failure of structural elements was evaluated by conducting double tension tests on large-size specimens. A sketch of the specimen and an adopted design scheme used for determination of the critical stress intensity coefficients are shown in Fig. 1. The brittle crack was initiated by cooling and breaking element 1 welded to a lateral edge of the tested portion of the specimen as a result of its tensioning by means of a special device. In this process a certain level of stresses was provided in the tested portion of the specimen by extending it at a given load. The variation in load and temperature values allowed determining the critical "temperature-stress" ratio at which the brittle crack did not propagate into the gauge length of the specimen.

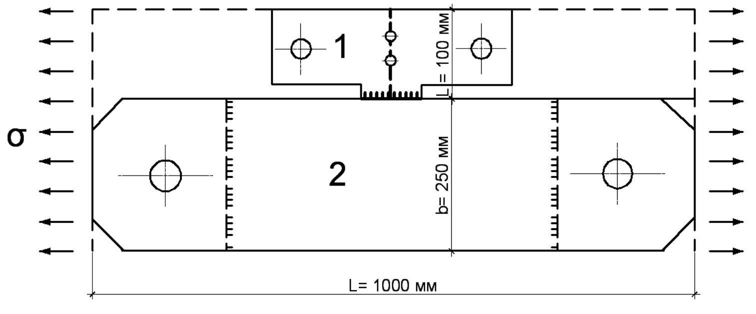


Figure 1: Test specimen for brittle crack arrest and design scheme used for determination of K_{co}.

The dependence of critical stresses corresponding to the crack arrest at a given temperature was determined on the basis of the test data obtained for the series of the test specimens. For calculation of the critical stress intensity coefficients a design scheme was adopted corresponding to the extension of the element having a side crack with the length being equal to the initiator width (Basko and Gusev [4]). For the design scheme the stress intensity coefficient is determined by formula

$$K_{do} = M \cdot \sigma_{do} \left(1 - \ell/b\right)\sqrt{\ell} \tag{1}$$

where M - dimensionless function ℓ/b;

σ_{do} - stress in the specimen at the brittle crack arrest;

b - width of the specimen gauge portion;

ℓ - length of the brittle crack.

The values of K_{do} were determined to evaluate the influence of the length of brittle cracks on critical temperatures of the crack arrest and to compare them with characteristics of the resistance to the failure under dynamic loading. The typical dependences of failing stresses on temperatures for St3sp low-carbon steel specimen under static loading are presented in Fig. 2.

3 Test data

The test data show that with a decrease in the temperature the failure occurring under conditions of developed plastic deformation over the whole specimen cross-section at the stresses in excess of the steel yield strength transforms into that occurring at elastic nominal stresses. The critical brittle temperature $T_{к2}$ determined by the equality of failing stresses for the yield strength greatly depends on the type of loading, size of the cross-section and length of the crack.

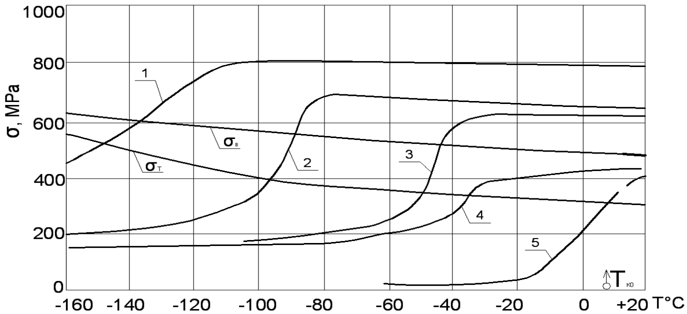


Figure 2: Temperature dependences of failing stresses under static bending (1, 2, 3), tension (4) and double tension (5) for specimens made of steel St3sp, t = 25 mm. Specimen cross-sections: 1 – 10x10 mm; 2 – 25x65 mm; 3 – 25x250 mm; 4 – 25x120 mm; 5 – 25x350 mm.

For instance, for the specimens with 10x10 mm cross-section and the crack as deep as 2.0-2.5 mm the value of $T_{к2}$ is –140÷150°C. When the cross-section size increases to 65x25 mm and the crack length ℓ = 25 mm the critical brittle temperature $T_{\kappa 2}$ increases by more than 60°C and is equal to –90÷100°C. With an increase in the test specimen width to 250 mm for a bending test on specimens with the crack length ℓ = 25 mm the transition to the brittle failure takes place at the temperature of 50°C below zero that is close to the range of climatic negative temperatures at which the use of low-carbon structural steel for building structures is allowed. When the test specimens are under tension the critical temperatures of the transition to brittle failures are somewhat higher and with a 40 mm long crack these are –25÷30°C. Nominal failing stresses in brittle states are 170-200 MPa.

The same diagram shows the dependences of the failing stresses σ_{co} on the temperature which were obtained from the tests on the specimens with the initiation of brittle cracks. As can be seen on the diagram the critical temperature of brittle crack arrest $T_{\kappa o}$ at nominal stresses approaching the steel yield strength for 20-25 mm thick structural mild steel elements is 10÷15°C. In the range of climatic negative temperatures the nominal stresses at which the arrest of brittle cracks is possible decrease to 20-25 MPa. Similar results were obtained when testing 10HSND steel specimens with the thickness of 20 mm for which the transition temperature of brittles failures of the specimens with cracks subjected to static tension was –55°C, and the critical temperature of brittle crack arrest is –25°C. For the case of brittle cracks arrested at the temperature below –40°C the failing stresses decrease to 25-30 MPa. A significant increase in the critical brittle temperatures and a decrease in the failing stresses at the propagation of brittle cracks is defined by a high strain rate at the crack tip. In this regard the characteristics of the resistance to the failure are in agreement with the appropriate characteristics of the material under dynamic loading that, in particular, can be seen from the data given in Fig. 3.

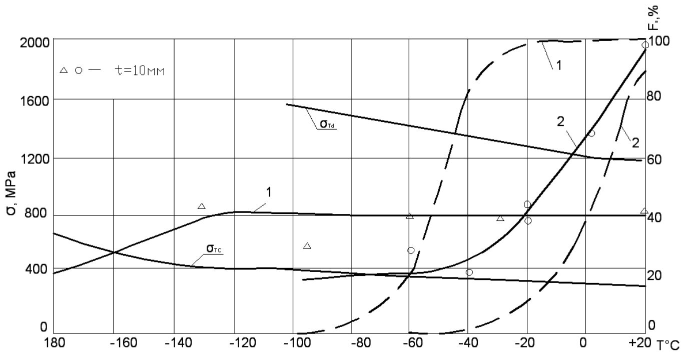


Figure 3: Temperature dependences of failing stresses and ductile component in fracture under static (1) and impact bending (2) of 10x10 mm specimens; 3, 4 – conditional yield strengths for static and dynamic tension.

Figure 3 shows that for impact loading the transition to brittle failures at the stresses below the yield strength takes place at the temperatures which are about

150ºC higher than those observed for static loading of the same test specimens. The temperature decrease range for the failing stresses and for the portion of ductile component in fractured specimens coincides with that for the critical stresses at the propagation and arrest of brittle cracks. Failing stresses occurring in brittle states under dynamic loading are higher than those occurring during double tension tests that is related to the difference in the crack lengths and loading conditions. In the area of ductile and quasi-ductile states force, strain and energy characteristics of the failure are higher than those for static loading that may just be a precondition for a possibility of arresting brittle cracks in structural elements.

To evaluate the influence of the scale factor on characteristics of the resistance to the brittle failure tests were carried on 20-40 mm thick steel specimens using the vertical hammer with the dropping weight.

Figure 4 presents the dependences of the levels of absorbed energy and the portion of the ductile component in fractured low-carbon specimens of the cross-sections 10x10 mm and 25x65 mm and with a 25 mm long crack. It follows from the data shown in the Figure that the cross-section sizes make a substantially different influence on the value of unit absorbed energy in ductile and brittle states. In the area of ductile failures the unit absorbed energy for full-thickness size specimens is 1.5÷1.7 times more than the corresponding values for Charpy-type test specimens with a fatigue crack that is determined by an increase in the volume of plastically deformed material and the corresponding increase in the value of absorbed energy. With a decrease in a degree of plastic deformation the influence of the scale factor on the unit absorbed energy decreases, and at the temperatures below $T_{к2}$ the value $\alpha_т$ depends neither on the size of the specimen cross-section nor on the crack length.

Similar dependences for 20-40 mm thick test specimens made of steel 10HSND are presented in Fig 4, A, B. As one can see from the given data the decrease in the unit absorbed energy under dynamic loading takes place in the same temperature range as for brittle crack arrest tests.

The results of the double tension tests with a brittle crack arrest can be presented as “temperature-unit absorbed energy” dependence. Taking the recoverable strain work of the tension specimen per cross-sectional area as equal to the unit propagation energy of the brittle crack we obtain

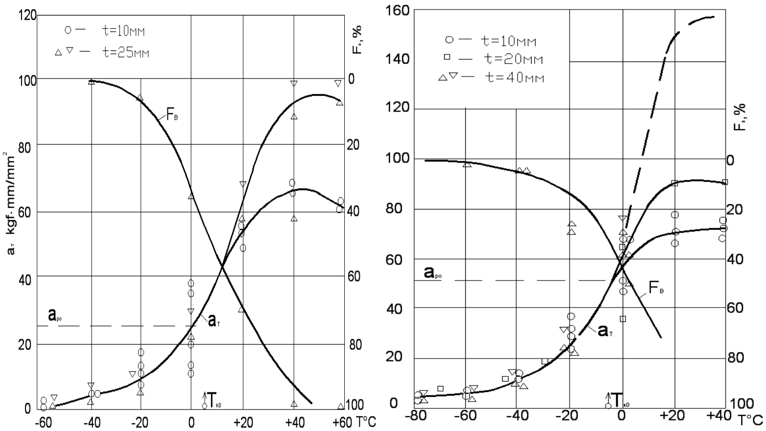
$$\alpha_p = 0.5\,\sigma_p^2 \cdot L/E \tag{2}$$

where L - test specimen length;

E - elastic modulus.

Substituting the values σ_p = $\sigma_т$ we obtain the values of α_p used for determination of the critical temperature of the brittle crack arrest. For St3sp low-carbon steel the values of $\sigma_т$ = 330 MPa, α_p = 25.9 kg/mm and for 10HSND steel – with $\sigma_т$ = 460 MPa, α_p = 50.5 kg/mm. As follows from the impact tests and tests by the dropping weight the temperatures corresponding to the obtained design values of α_p are about 5°C and –10°C for the steel grades St3sp and

10HSND, respectively. Within the inaccuracy of measurement of failure parameters these values correspond to those of $T_{ко}$ for double tension tests.



A B

Figure 4: Temperature dependences of unit absorbed energy and ductile component in fracture for impact bending of specimens made of steels St3sp (A) and 10HSND (B).

The values of critical stress intensity coefficients K_c and K_d were calculated using the test data for the specimens with cracks under static and dynamic loadings. Temperature dependences of the characteristics of cracking resistances K_c and K_d for the steels St3sp and 10HSND are shown in Fig. 5, A, B. As can be seen the minimum values of static and dynamic cracking resistance are 15.0 MPa$\sqrt{\text{m}}$ for the steel St3sp and 25 MPa$\sqrt{\text{m}}$ for the steel 10HSND. With an increase in the temperature the values K_c and K_d increase. In the range of climatic negative temperatures the value K_c exceeds 2.5-3.0 times that of K_d. The values of dynamic cracking resistance obtained for Charpy tests on specimens with a fatigue crack and on 20-40 mm thick large flat specimens coincide with those obtained for failures with a prevailing crystal fracture.

In the field of ductile states the characteristics of dynamic cracking resistance are greater than the corresponding characteristic values for static loading that is linked with a substantial increase in the dynamic limits of the yield strength of steels which keep their ability to plastic deformations. Therefore under conditions of dynamic actions the maximum failure resistance is provided by the use of materials demonstrating a high ability to plastic deformations at minimum service temperatures.

4 Case studies

In conclusion we give some examples of using the characteristics of cracking resistance obtained for static and dynamic loadings in the evaluation of the resistance to a brittle failure of steel structures.

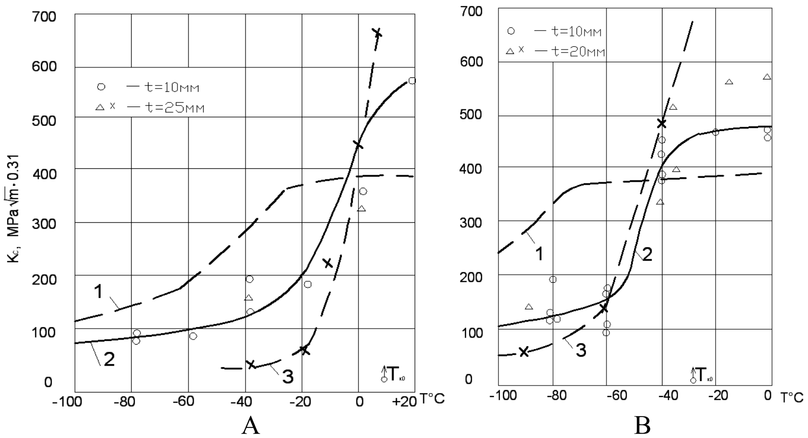


Figure 5: Temperature dependences of cracking resistance limits for static (1), dynamic (2) loading and brittle crack arrest test (3) of steels St3sp (A) and 10HSND (B)

In a spherical gasholder made of 09G2S low-carbon steel with the diameter of 16 m and the shell thickness of 36 mm a 300 mm long through crack was discovered as a result of a product leakage occurred 20 days after the gasholder was commissioned (Vasutin and Demygin [5]). According to the data provided by a regional meteorological service, the outside air temperature did not fall below –16 ^{o}C for this time period. As the fracture analysis showed the failure had started from the surface of poor penetration having the length of 74 mm and depth of 10 mm. The poor penetration was a narrow slit between weld passes that was filled with slag. The crack propagated in a jump-like manner from the equatorial weld into the base metal. The fracture was of crystal structure. The crack went into the base metal and stopped in it. The results of the double tension tests showed that at the temperatures of –18 ^{o}C the critical stress was 100 MPa. The maximum working pressure in the gasholder was 1.2 MPa. At this pressure the nominal stress in the gasholder shell was σ_{H} = 133 MPa. It is evident that the leakage was found when the value of nominal stresses did not exceed 100 MPa that corresponds to the internal pressure of 0.9 MPa.

Based on the test data for the specimens with a crack made of steel 09G2S subjected to bending at the temperature of –20 ^{o}C the value of K_d is 80 MPa $\sqrt{\mathrm{m}}$. Determining the stress intensity coefficient for this case we obtain

$$K_1 = \sigma_\alpha \sqrt{\pi \cdot \ell} = 100\sqrt{3.14 \cdot 150 \cdot 10^{-3}} = 68.5\ \mathrm{MPa}\sqrt{\mathrm{m}} < K_d = 80\ \mathrm{MPa}\sqrt{\mathrm{m}}.$$

Thus a large brittle failure of the gasholder was avoided owing to the fact that the crack jump had occurred either at the temperature above –20^{o}C or at the internal pressure not exceeding 1.0 MPa.

The case study of a total failure of a 5,000 m^3 storage capacity vertical cylindrical tank (Rosenstein and Vompe [6]) can also be analysed using the characteristics of dynamic cracking resistance. The tank with the height of 12 m and diameter of 22.8 m failed when it was fully filled with a product at the outside air temperature below –34°C. The temperature of the tank shell determined by the calculation taking into account heat emission was –10°C. The tank shell is made of low-carbon steel St3sp. The shell thickness of the tank first course where a brittle crack formed is t = 10 mm. The analysis of the failed surface revealed that the brittle crack had occurred as a result of poor penetration in the hatch shell. The crack went through its shell propagating into the base metal of the first course and the hatch collar. Then it propagated in the full height of the tank shell. The results of the tests with the initiation of a brittle crack showed that at the temperature of –10°C the crack arrest in the shell of the first course is possible at nominal stresses which are not higher than 60 MPa. For the fully filled tank design stresses in the shell of the first course σ_H = 170 MPa. At the shell temperature of –10°C the dynamic limit of cracking resistance K_d = 40 MPa$\sqrt{\text{m}}$. For the thickness of the hatch shell t = 8 mm the length of the initiated brittle crack with respect to the leg and the area of embrittled metal in the shell of the first course could be 18-20 mm.

At the design stresses in the shell of the tank first course σ_H = 170 MPa we obtain

$$K_1 = M \cdot \sigma_H \sqrt{\ell} = 2.0 \cdot 170\sqrt{20 \cdot 10^{-3}} = 47.94 \quad \text{MPa} > K_d = 40.0 \quad \text{MPa}\sqrt{\text{m}}.$$

Another important factor that triggered the brittle failure might have been the low temperature of the shell near the hatch for which the limit of steel dynamic cracking resistance is accordingly lower.

On the whole the described study cases of the brittle failure demonstrate a possibility of evaluating the resistance to a brittle failure of steel structures with the use of the dynamic limits of cracking resistance for structural steels.

5 Conclusions

Based on the obtained results of the experimental studies and the analysis of the structural steel failures the following conclusions can be made:

1. Large-size steel structures made of low-carbon structural steels which are in service at climatic negative temperatures run the risk of brittle failures under external or internal dynamic effects;
2. One of the most effective methods of increasing the resistance to brittle failures of steel structures under dynamic effects is the use of good quality structural steels and welding materials with critical brittle temperatures which are below minimum service temperatures for dynamic loading;
3. The design evaluation of the resistance to brittle failures of steel structures considering dynamic effects is possible when using dynamic

limits of steel cracking resistance determined during impact tests on specimens with cracks.

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