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Methods for Brittle-Fracture-Resistant Structural Material Selection Based on Polish and International Standards – Part 2

Abstract: The article describes the phenomenon of the brittle cracking of steel as a component of structural elements of pressure equipment and construction products. The study presents several methods of analysis used by specialists responsible for the design, fabrication and testing of the aforesaid products. The article also indicates numerous international regulations, standards and recommendations used in the assessment of the strength of various structural elements and technical solutions. The methods discussed in the study were compared to enable the selection of sophisticated material assessment methods ensuring the superior functional properties and safe operation of finished products.

Key words: brittle fracture, materials, pressure equipment, construction products

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1. Introduction

The first part of the article, in addition to the introduction to the subject, contained examples based on standards harmonised with the Pressure Equipment Directive. In turn, the second part discusses the application of fracture mechanics and the analysis of the resistance of construction products to brittle fracture.

In terms of fracture mechanics, the assessment of the strength of a structural element containing a defect will be based on FITNET procedures [12] (referred to in the first part of the article). The FITNET procedures are primarily based on SINTAP procedures published in 1999. Analysis based on the FITNET procedures [12] requires the use of a full algorithm involving material definition, structure selection, defect definition and the selection of analysis path. The final result of complete analysis is the answer to a question concerning the safety of a given structure made of specific material, containing a specific defect and affected by a given load. Another question which needs to be answered is whether the operation of the structure should cease immediately or could be continued. The answers to these questions are usually obtained by analysing related failure diagrams [12].

The analysis of resistance to brittle fracture is based on the method presented in standards [9, 10]. In accordance with the methodology proposed in normative documents [9, 10], it is assumed that the design temperature of an element which could undergo brittle fracture is higher or equal to the temperature limit responsible for safe brittle fracture resistance under specific conditions. Such an approach facilitates the analysis and leads to the obtainment of conservative results.

2. Application of fracture mechanics analysis

Apart from fatigue, creep and corrosion, fracture mechanics in the FITNET procedures [12] constitutes one of the four major modules. The most general schematic diagram of fracture mechanics is presented in Figure 3, contained in the first part of the article. The use of the fracture mechanics module requires knowledge concerning the shape of a structural element and its dimensions, the manner of loading, the shape of defect(s), material characteristics as well as knowledge of whether the structural element is welded or made of a homogeneous material. All the above-presented information affects analyses necessitating the use of existing solutions to estimate the ultimate load capacity (ultimate loads), the current value of stress intensity factor indicating fracture resistance and the choice of the method of analysis, necessary to determine the failure curves of the Failure Assessment Diagram (FAD) or Crack Driving Force Diagram (CDF).

As already mentioned, an academic textbook published by the Kielce University of Technology [5] is concerned with the FITNET procedures in Poland. In several works by Jarosław Gałkiewicz and Marcin Graba [2], the Authors presented a FITNET.exe program (based on the FITNET procedures) enabling the analysis of structures containing a defect(s) or the analysis of a structural element exposed to fatigue loads. The first joint work of the above-named Authors was presented at the National Conference on Fracture Mechanics in 2007 [2]. In the subsequent years, the program was presented individually by the Authors at international conferences on fracture mechanics (Augustów 2009 – [1, 2, 4]), at a seminar on the strength, durability and

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safety of systems and structural elements organised by the Stanisław Staszic Foundation in Kielce and the Kielce University of Technology in 2009 as well as at the Polish Academy of Sciences Meeting on Mechanics in 2010, organised by the Kielce University of Technology.

The FITNET.exe program contains predefined databases of selected materials and libraries of formulas enabling the estimation of ultimate loads, stress intensity factor values and the values of residual stresses. In addition, the programme can be used for drawing appropriate failure curves in accordance with the FAD or CDF.

The use of FITNET procedures in the assessment of brittle fracture is fully justified [5]. Simple empirical formulas make it possible to relate the above-named material toughness to the stress intensity factor, regardless of the location of the toughness value on the brittle-plastic transition curve of the material subjected to tests. The FITNET procedures can be successfully used to estimate the temperature

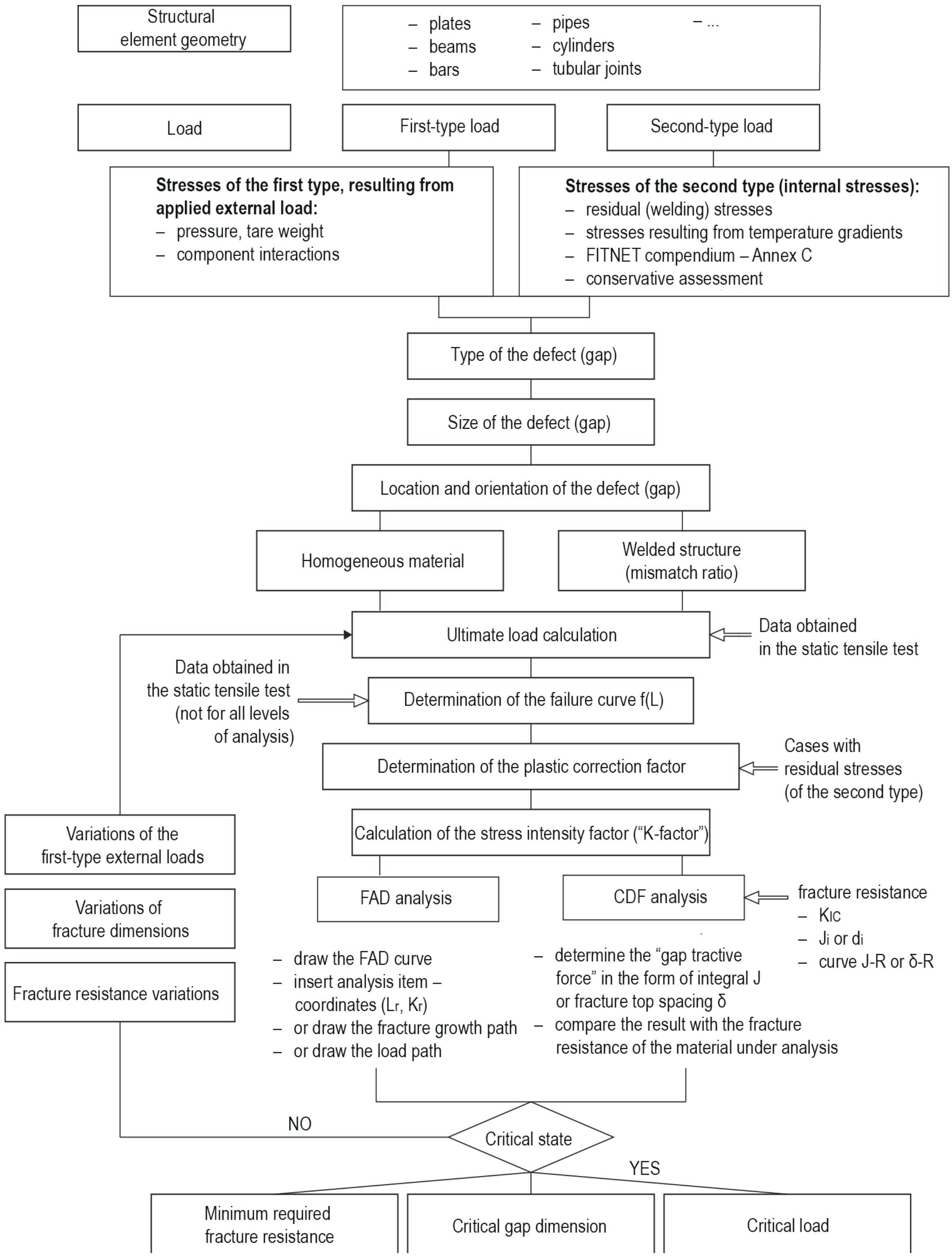

Fig. 1. General schematic diagram of the fracture mechanics module in the FITNET procedures (own elaboration based on [12])

at which impact energy reaches 27 J. The aforesaid estimation requires the use of a table presenting a change in the previously assumed impact energy as a function of the difference between the temperature of analysis and the temperature of transition at which the value of impact energy reaches 27 J.

Using available empirical correlations, it is possible to convert material toughness into the stress intensity factor, the critical value of which is considered to control the brittle fracture process. Afterwards, using many ultimate-load-related solutions and the FAD diagram, it is possible to assess whether the detected/hypothetical defect poses a threat to the structure subjected to analysis.

As part of the presentation of the capabilities of the FITNET procedures, the following subsection contains a solution of a practical example based on the FITNET procedures and the FITNET.exe computer programme, co-authored by one of the Authors of this article.

2.1. Application of FITNET procedures to pressure equipment

The presentation of the possibilities of the FITNET procedures involves the presentation of a solution to a practical problem, i.e. the determination of the strength of a pipe containing an internal transverse surface fracture (Fig. 2a). The subject of the analysis was a pipe with external diameter R_0 = 70 mm and wall thickness B = 5 mm (internal diameter R_i = 60 mm). The pipe was a component of a transmission pipeline operating under pressure at a temperature of approximately 20 °C. The pipeline was supported (at certain distances) by several 2.5 m high pillars. The (hypothetical) inspection of the system revealed the appearance of an irregularly-shaped transverse (circumferential) surface defect, which, for the purposes of engineering analysis, could be idealised as an internal transverse semi-elliptical fracture having depth a = 3.5 mm and length $2c$ = 37 mm, corresponding to the angle of the position of the outermost fracture points amounting to approximately 30°. Engineering analysis, performed when the fracture was detected made it possible to estimate the distribution of stresses across the pipe wall thickness in the fracture plane (presented in Fig. 2b). It was assumed that the stresses in the cross-section of the pipe subjected to analysis changed linearly from 325 MPa to 375 MPa. The pipe was made of alloy steel 1.0562 (or 18G2A in accordance with the old PN-based designation) having conventional yield point $R_{0.2}$ = 343 MPa, tensile strength R_m = 550 MPa and strain-hardening coefficient in the R-O (Ramberg--Osgood) law amounting to n = 8. The fracture toughness was K_{mat} = 128 MPa·m$^{0.5}$ [5]. The assessment of the strength of a hypothetically selected pipe would require the use of numerous formulas from fracture mechanics and the strength of materials, enabling the estimation of the ultimate load, the stress intensity factor in relation to the identified defect as well as formulas required for the plotting of failure curves (FAD). Instead of the performance and subsequent description of the above-named activities, the presentation concerns the procedure involving the use of the FITNET.exe program with predefined libraries, helping to solve the aforesaid type of engineering problems.

The start of the FITNET.exe program is followed by the appearance of the welcome window (the subsequent screenshots of the application are presented in Fig. 3), enabling the user to perform further analysis (Fig. 3a). In order to define geometry, it is necessary to select the "Defect" button and define the type of structure; the buttons presented in Fig. 3b correspond to the problem under consideration. Figures 3b and 3c present the subsequent stages concerning the identification of the shape of a structure. The identification of the shape and the determination of whether the structural element was welded or not should be followed by the selection of material. In relation to the shape under consideration, the material was selected from the predefined library of the FITNET.exe programme (Fig. 3e). By clicking the "First-type stresses" button, the user can load the stresses measured in the cross-section of the fracture (Fig. 3f). The final step involves the performance of the FAD analysis (Fig. 3g-h). The programme automatically determines failure curves (FAD) and selects the appropriate formulas enabling the estimation of the ultimate load and stress intensity factor concerning the defect under consideration. The calculation results are presented in the graphical form as FAD charts as well as in the numerical form as the coordinates of the point subjected to analysis (L_r and K_r), i.e. the purple point in Figures 3h and 4. In addition, the program automatically calculates margin (reserve) factor F_p, which, assuming a value of <1 in relation to a given level of analysis, indicates a potentially safe situation.

Based on the FITNET procedures, the calculated coordinates of the analysis point corresponding to the load were normalised external load L_r = 1.077 and normalized stress intensity factor K_r = 0.574. As could be seen, the load affecting the structural element exceeded the ultimate load value. In turn, in relation to the zero, first and second level of analysis, it was possible to speak of the potential destruction of the structural element as the point of analysis having coordinates (L_r, K_r) was located to the right of the destruction curves [i.e. outside the area limited by the destruction curves and the coordinate system axes (Fig. 4)].

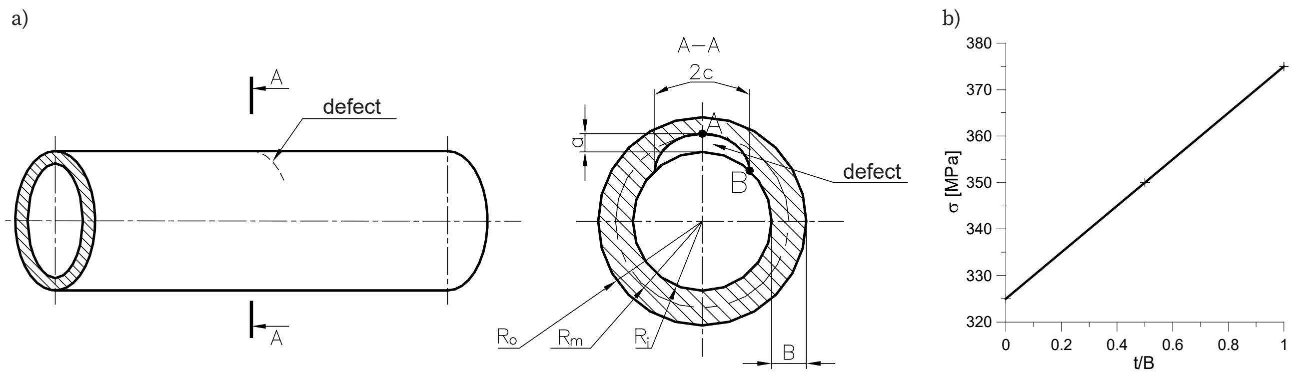

Fig. 2. Schematic diagram of a pipe containing an internal transverse surface fracture (own elaboration based on [2, 4, 5, 12])

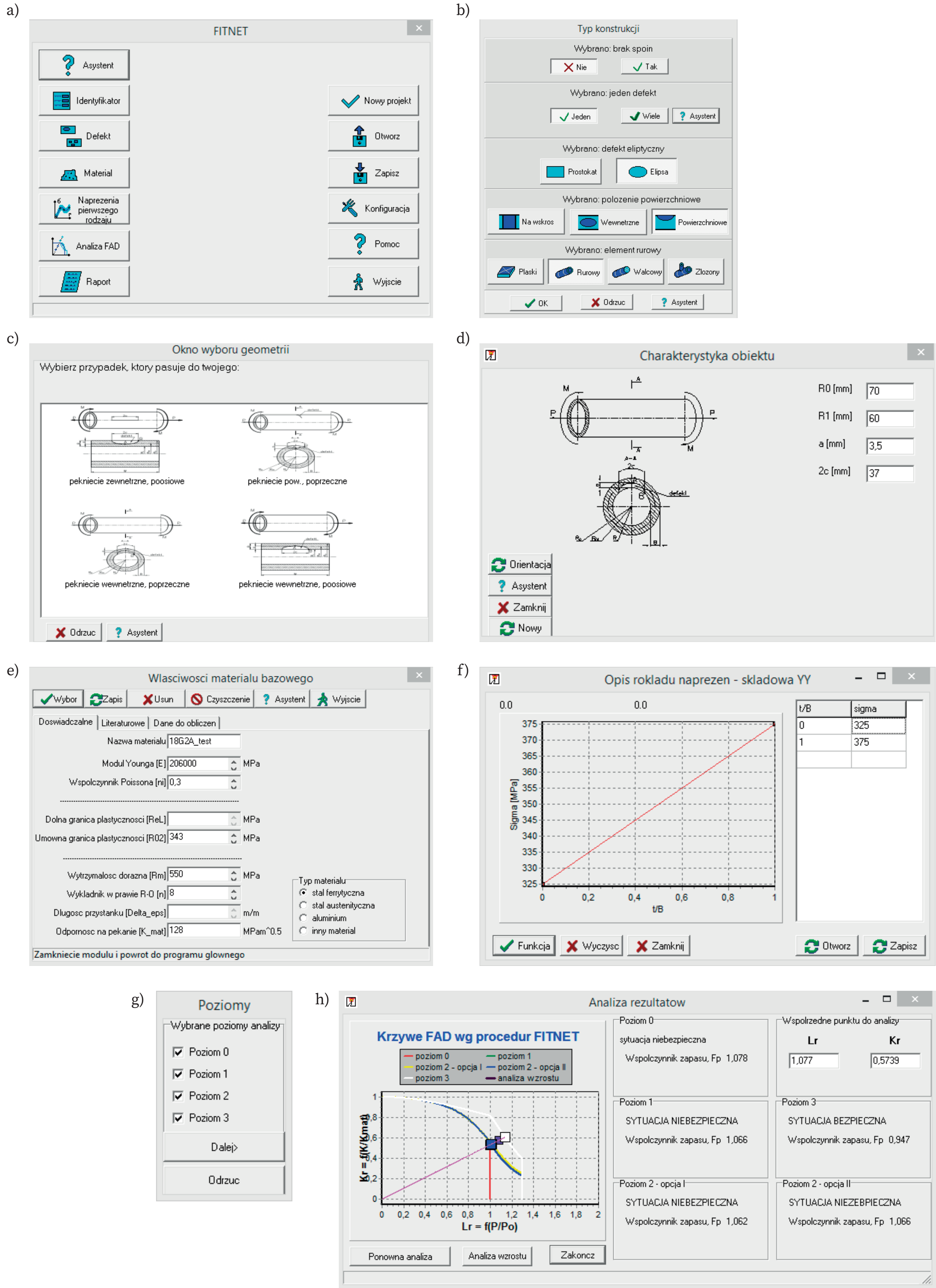

Fig. 3. Subsequent stages of the assessment of the strength of the pipe containing an internal transverse surface fracture in accordance with the FITNET procedures; the assessment was performed using the FITNET.exe programme (own elaboration based on [1, 2, 4, 5 and 12])

FAD curves in accordance with the FITNET procedures

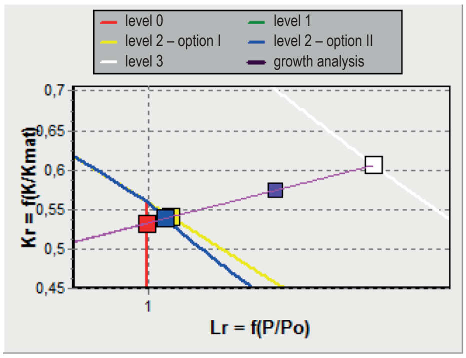

Fig. 4. Fragment of the FAD diagram used in the assessment of the strength of the pipe containing the internal transverse surface fracture (in accordance with the FITNET procedures); the assessment was performed using the FITNET.exe application (the purple point on the diagram corresponds to coordinates (L_r and K_r) (own elaboration based on [1, 2, 4, 5 and 12])

The analysis of sensitivity indicated the necessity of reducing the external load by approximately 8 %. The aforesaid change in the position of the point of analysis might change the situation from hazardous to safe.

The reference of the point of analysis to the FAD curve at the third level of analysis indicated a safe situation as the aforesaid point was located to the left of the FAD curve in relation to the third level of analysis (i.e. within the area limited by the FAD curve related to the third level of analysis and the axes of the coordinate system). The sensitivity analysis in relation to the third level of analysis indicated a possibility of an increase in the external load by approximately 6 %.

3. Legal requirements concerning construction products

In most cases, construction products launched in the European Community market have to, in most cases, be marked with the CE marking confirming their compliance with the essential requirements contained in the standards harmonised with Regulation (EC) No 305/2011 of the European Parliament and of the Council (Construction Products Regulation – CPR). The regulation has established harmonised conditions for the launch of construction products. In accordance with the regulation, a construction product is any product or a set manufactured and launched in the market for the purpose of its permanent incorporation into a building/structure or its parts, where the properties of such a construction product affect the performance of buildings in relation to the basic requirements applying to buildings [13].

The products specified in the CPR include lampposts, building hardware, radiators and convectors, steel and aluminium structures of buildings and structures, structural bearings, elements of structural ceramics, thermal insulation systems, roofing systems, etc.

3.1. Requirements for materials used in construction products

Initial information concerning materials used in steel or aluminium structures was provided in the introduction to this part of the article. The information indicates some general characteristics of welded materials used in the fabrication of given structures. Detailed characteristics are discussed in relation to materials used in construction products made of hot-rolled steels and specified in the PN-EN 10025-1 series of standards [9]. Because of being used in general and industrial building engineering, the above-named materials are referred to as structural steels although they are also used in the production of machines (particularly those having large dimensions) as well as pressure equipment. In the latter case, these are certain structural steel grades of strictly defined physicochemical and mechanical properties.

The most important features of structural steels are their mechanical properties, i.e. yield point R_e (usually, upper yield point ReH is determined), tensile strength R_m, impact energy *KV* (sometimes determination concerns toughness, i.e. impact energy related to the cross-section of the specimen), elongation at rupture A_5 or A_{10} and area reduction *S*. The above-presented features determine the load-bearing capacity of structures [3].

3.2. Example of a standard harmonised with the CPR regulation

The definition of a harmonised standard is provided in section 3.2 of the first part of the article. Several hundred standards have been harmonised with the CPR regulation. The aforesaid standards are most often used by manufacturers of various types of construction products or manufacturers fabricating materials used in the production of construction products. An example of the aforesaid standard is the PN-EN 10025-1 standard, [9], specifying requirements for flat products and hot-rolled long products made of unalloyed structural steels. The standard does not contain requirements concerning hollow sections and pipes. The standard refers to many other normative documents (in particular to parts 2–6) containing detailed requirements for unalloyed steels, fine-grained steels after normalisation or normalisation rolling, fine-grained steels after thermomechanical rolling, steels with improved corrosion resistance and steels with increased yield point in the quenched and tempered condition. The list of the PN-EN 10025 series of standards is presented in Table 1. It should be noted that the PN-EN 10025 series of standards is usually applied to the construction of buildings and structures, yet also contains requirements concerning materials used in the fabrication of machines such as cranes, vehicles, pressure equipment, etc. The steel grades specified in the above-named series are widely available not only in European countries but also in other markets, where the above-named products or semi-finished products are used in subsequent works.

3.3. Requirements specified in the PN-EN 1993-1-10 and PN-EN 1993-1-12 standards

As mentioned in Section 3.4, brittle fractures are formed as a result of stress concentration, low temperature and the presence of notches. The selection of structural steel with respect to its resistance to brittle fracture and interlayer ductility is based on two standards. The PN-EN 1993-1-10 [7] standard is concerned with steel grades S235 to S460, whereas the PN-EN 1993-1-12 [8] standard is related to steel grades S500 to S700. It should be mentioned that the procedures specified in the above-named standards apply if a given structure is made in accordance with the PN-EN 1090 series of standards.

Table 1. Parts of the PN-EN 10025 standard – Hot-rolled products of structural steels [9]

Part	Name	Subject/steel group
1	Hot-rolled products of structural steels	General technical delivery conditions
2		Technical delivery conditions for non-alloy structural steels
3		Technical delivery conditions for weldable fine grain structural steels after normalisation/normalisation rolling
4		Technical delivery conditions for weldable fine grain structural steels after thermomechanical rolling
5		Technical delivery conditions for structural steels with improved atmospheric corrosion resistance
6		Technical delivery conditions for flat products of high yield strength structural steels in the quenched and tempered condition

The method proposed in the aforementioned standards [7, 8] (used to determine the permissible thickness of steel elements) is based on the following parameters:

- steel grade,
- steel quality group, determined on the basis of impact energy,
- structural element effort,
- element ambient temperature, including the temperature of the element itself.

The assessment of the resistance of materials to brittle fracture in relation to the PN-EN 1993-10 and PN-EN 1993-12 standards [7, 8] involved the application of fraction mechanics, in accordance with the inequality presented below [6]

$$K^{*}_{appl,d} \leq K_{mat,d} \tag{1}$$

where:
$K^{*}_{appl,d}$ – stress intensity factor, determined in relation a given structural element,
$K_{mat,d}$ – coefficient of material resistance to brittle fracture.

The methodology used in the standards [7, 8] enables technicians and engineers to perform design calculations based on a series of calculations which, in turn, are based on tabular data. The collection of the aforesaid data should not pose any problem because, in most cases, the data can be found in the standards and related documents.

The principles governing the specification of requirements in relation to the aforementioned structural materials refer to the products provided in the PN-EN 1993-1-1 standard. The guidelines contained in the PN-EN 1993-10 and PN-EN 1993-12 standards [7, 8] should be used when selecting steel grades for new structures. It is recommended that the guidelines be used in elements exposed to tensile stresses and welded elements exposed to variable fatigue loads. In any other case of the load pattern, it is recommended that direct fracture mechanics be used as a significantly less conservative method of analysis if compared to that included in the above-named standards.

3.4. Method presented in the PN-EN 1993-1-10 and PN-EN 1993-1-12 standards

The method described in the PN-EN 10025-1 and PN-EN 10025-2 standards [9, 10] is based, among others, on the analysis of the temperature at which a given structure is operated. Such an approach simplifies the entire analytical process. In accordance with the aforementioned approach, it is assumed that the design temperature of the element which may undergo brittle fracture could be higher than or equal to the temperature limit corresponding to the safe level of resistance to brittle fracture under specific conditions. The relationship is provided below:

$$T_{Ed} \geq T_{Rd} \tag{2}$$

where:
T_{Ed} – design temperature of the structural element,
T_{Rd} – temperature limit corresponding to the safe level of resistance to brittle fracture under specific conditions.

The method provided in the standards is divided into stages and presented below in several subsections, containing the rules of selection based on available input data in relation to specific design solutions.

3.4.1. Selection of steel grades and their quality groups [7]

The selection of a given steel grade and its quality group begins with the verification of the steel properties described in the inspection document issued by the steel manufacturer (in accordance with the conditions specified in the PN-EN 10204 standard). The document should contain (at least) the following information:

- yield point (strength), specified in relation to the thickness of the product $f_y(t)$,
- minimum impact energy, specified in relation to a given temperature.

The subsequent stage involves the determination of the characteristics of the part (subjected to analysis) as a structural element. The elements of the characteristics are the following:

- shape and details of the structural element,
- concentration of stresses in accordance with the categories specified in the PN-EN 1993-1-9 standard,
- greatest thickness among those of the components of the structural element t as a single metallurgical product,
- expected permissible imperfections which could form during the fabrication or operation of a given structure, e.g. fractures across the thickness or semi-elliptical surface fractures.

The next stage involves the definition and identification of design values and parameters leading to the obtainment of dependence (2):

- design value of the lowest expected temperature of the structural element,
- greatest stresses originating from constant and variable loads, resulting from the calculation (design) conditions described below,

- internal stresses of the structural element,
- assumed propagation of fatigue cracks during the structure- or structural-element-related inspection periods (if applicable),
- increase in strain $\dot{\varepsilon}$ originating from incidental loads adopted for analysis (if applicable),
- degree of cold forming ε_{cf}, based on the manufacturing process (if applicable).

3.4.2. Permissible thickness of elements with regard to brittle fracture

The maximum permissible thicknesses of elements (in relation to the grade and quality group of selected and most frequently used structural steels) are presented in Table 2.1 in the PN-EN 1993-10 standard [7]. Table 4 in the PN-EN 1993-12 standard [8] presents toughened (quenched and tempered) steel grades having an increased yield point and thermomechanical steels subjected to thermomechanical treatment. The above-named information is used at the final stage of analysis, to compare the thickness calculated at the design stage with thicknesses specified in related standards. The values in the tables were developed on the basis of the following assumptions:

- values corresponded to the reliability-related specified in the PN-EN 1990 standard in relation to ordinary-quality steel grades,
- adopted strain rate $\dot{\varepsilon} = 4 \cdot 10^{-4} \cdot s^{-1}$ of the structural element took into account the effects of dynamic (mostly transient) interactions as well as constant conditions covered by calculations. In relation to other strain rates $\dot{\varepsilon}$ (e.g. in cases of impact loads or any quick-changing loads) it is possible to use the values provided in the tables. When doing so, design temperature T_{Ed} should include negative component $\Delta T_{\dot{\varepsilon}}$ (°C), expressed by the following formula:

$$\Delta T_{\dot{\varepsilon}}(t) = -\frac{1440 - f_y(t)}{550} \cdot \ln\left(-\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right) \tag{3}$$

- it was assumed that the material was not cold-strained, where $\varepsilon_{cf} = 0$ %. In terms of unaged cold-strained steel grades, it is possible to use the values provided in the tables, where design temperature T_{Ed} should include negative component $\Delta T_{\dot{\varepsilon}}$ (°C), expressed by the following formula:

$$\Delta T_{\varepsilon cf} = -3\varepsilon_{cf} \tag{4}$$

- nominal values of impact energy expressed as T_{27J} and provided by the manufacturer of the material were adopted from the PN-EN 10025, PN-EN 10210-1 and PN-EN 10219-1 application standards. In relation to other values, the conversion applied was the following:

$$\begin{aligned} T_{40J} &= T_{27J} + 10\ °C \\ T_{30J} &= T_{27J} + 0\ °C \end{aligned} \tag{5}$$

- taking into account all the fatigue categories (of elements) provided in the PN-EN 1993-1-9 standard. In addition, when considering the fatigue load, it was assumed (in the analysis) that the load affected the structural element containing an initial imperfection. The adopted value (in accordance with the PN-EN 1993-1-9 standard) constituted a fourth of the total fatigue failure. The foregoing enabled the adoption of the assumption that the lowest number of "safe intervals" between scheduled inspections during operations would be specified in accordance with the PN-EN 1993-1-9 standard. The standard requires that the number (n) of inspections during operation and dependent on partial coefficients γ_{Ff} and γ_{Mf} (applied in fatigue-related calculations in accordance with the PN-EN 1993-1-9 standard) should be specified in accordance with the following formula:

$$n = \frac{4}{(\gamma_{Ff}\,\gamma_{Mf})^{m}} - 1 \tag{6}$$

where $m = 5$ in relation to structures with long operation times, e.g. bridges or overpasses
- Table 2.1 in the PN-EN 1993-10 standard [7] and Table 4 in the PN-EN 1993-12 [8] provide the maximum permissible thicknesses of elements for three stress levels defined in relation to the nominal yield point of the structural material in N/mm^2:

$$\begin{aligned} \sigma_{Ed} &= 0.75 f_y(t) \\ \sigma_{Ed} &= 0.75 f_y(t) \\ \sigma_{Ed} &= 0.75 f_y(t) \end{aligned} \tag{7}$$

- nominal yield point was calculated in accordance with the following formula:

$$f_y(t) = -f_{ynom} - \frac{0.25t}{t_0} \tag{8}$$

where:
t – design temperature of the structural element,
t_0 = 1 mm or the value of $f_y(t)$ was adopted as equal to upper yield point R_{eH} specified in related standards concerning steel products
- it should also be noted that (in practice) linear interpolation for intermediate values is applied. In most cases, the values of σ_{Ed} are restricted between $\sigma_{Ed} = 0.75 f_y(t)$ and $\sigma_{Ed} = 0.50 f_y(t)$. Weight function $\sigma_{Ed} = 0.25 f_y(t)$ was provided for interpolation-related needs. Extrapolation outside extreme values should not be applied. It should also be noted that Tables 2.1 and 4 were developed adopting the guaranteed values of impact energy in the (product) rolling direction.

3.4.3. Method based on the PN-EN 1993-1-10 standard – example

The calculation method in accordance with the PN-EN 1993-10 standard [7] is presented below. The method involves the determination of the maximum permissible thickness of the material used in the fabrication of a given structure. The aforesaid thickness depends on the lowest expected temperature of the structural material. The method makes it possible to determine the quality subgroup of steel. It should be emphasized that (in many cases) this method is conservative, yet, because of its simplicity, it enables the performance of quick analysis and verification of design assumptions.

Input data

The structure was located in the city of Kielce. The structural node was the T-joint. The beam (transom) was welded to the column with fillet welds. The column was reinforced with ribs made of a sheet having the same thickness as the beam flanges welded to the beam with fillet welds. The dimensions of the details along with the material data (based on widely applied European standards) are presented in Tables 2, 3 and 4. The schematic diagram of the arrangement of the details in the element along with related interactions is presented in Figure 5.

Table 2. Parameters of open sections in accordance with Euronorms 19-57 and 53-62 [11] (mm)

Element	Basic grade	Height	Flange height	Web thickness	Flange thickness	Remarks
HE 320 B	S355	320	300	11.5	20.5	–
IPE 450	S355	450	190	9.5	14.6	–

Table 3. Parameters of the IPE 450 section in accordance with Euronorms 19-57 and 53-62 [11]

Element	Basic grade	Cross-sectional area	Elastic sectional modulus	Remarks
IPE 450	S355	$98.8 \cdot 10^2$ mm^2	$1500 \cdot 10^3$ mm^3	–

Table 4. Design load values

Element	Basic grade	Siła osiowa	Moment gnący	Remarks
IPE 450	S355	$N_{Ed} = 95.5$ kN	$M_{yEd} = 250.7$ kNm	–

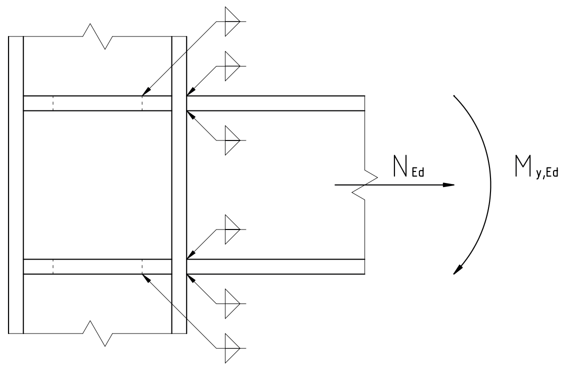

Fig. 5. Schematic diagram of the node with resultant loads

Design temperature of the element

The structure was located in the city of Kielce (in accordance with the PN-EN 1991-1-5 standard). The lowest possible standard temperature was the following:

$$T_{minN} = -30\ °C \tag{9}$$

Design temperature of the element in relation to the height above mean sea level

The location of the structure was the city of Kielce, where the highest point of the city was located at an altitude of 410 m:

$$T_{minHa} = \frac{0.0035}{m} \tag{10}$$

$$T_{minHb} = T_{minHa} \cdot 410 \cdot m \tag{11}$$

$$T_{minHb} = -1.4\ °C \tag{12}$$

$$T_{min} = T_{minN} + T_{minHb} \tag{13}$$

The lowest air temperature at the altitude of the element location, adopted in relation to the highest location point in the city of Kielce was the following:

$$T_{minHb} = -31.4\ °C \tag{14}$$

$$T_{md} = T_{min} \tag{15}$$

The radiation losses were the following:

$$\Delta T_r = -5\ °C \tag{16}$$

The correction taking into account the stresses and yield point of the element was the following:

$$\Delta T_\sigma = 0\ °C \tag{17}$$

The correction taking into account the safety margin was the following:

$$\Delta T_R = 0\ °C \tag{18}$$

The correction taking into account the strain rate was the following:

$$\Delta T_\varepsilon = 0\ °C \tag{19}$$

The correction taking into account the cold strain effect was the following:

$$\Delta T_{\varepsilon cf} = 0\ °C \tag{20}$$

The design temperature of the element was the following:

$$T_{ED} = T_{md} + \Delta T_r + \Delta T_\sigma + \Delta T_R + \Delta T_\varepsilon + \Delta T_{\varepsilon cf} \tag{21}$$

$$T_{ED} = -36.4\ °C \tag{22}$$

It was adopted that:

$$T_{ED} = -37\ °C \tag{22}$$

Calculation of stresses

The stresses in the node were determined from the beam (transom) side. The thickest element was the column flange, for which the highest stress and the lowest possible temperature were adopted. The temperature changes of the structure were determined in accordance with the conditions specified in the PN-EN 1991-1-5 standard and its national annex.

The greatest stresses originating from bending were the following:

$$\sigma_{Ed} = \frac{M_{yEd}}{W_{elyIPE450}} + \frac{N_{Ed}}{A_{IPE450}} \tag{24}$$

$$\sigma_{Ed} = 176.8\ \text{MPa} \tag{25}$$

Correction of greatest stresses

The PN-EN 1993-10 standard [7] recommends the adoption of the following reference thickness:

$$t_0 = 1\ \text{mm} \tag{26}$$

The calculations involved the thickest part of the elements, i.e. the column flange:

$$t_{max} = t_{FHE320B} \quad (27)$$

$$t_{max} = 20.5 \text{ mm} \quad (28)$$

In accordance with the PN-EN 10025-2 standard [10], the lowest yield point for steel S355 of the specified thickness amounted to:

$$f_{ynom} = 345 \text{ MPa} \quad (29)$$

The yield point in relation to the product thickness was the following:

$$f_y = f_{ynom} - \frac{0.25 \text{ MPa} \cdot t_{max}}{t_0} \quad (30)$$

The yield point in relation to the product thickness was the following:

$$f_y = 339.875 \text{ MPa} \quad (31)$$

The level of stresses and the level of stresses used in the calculations were the following:

$$\frac{\sigma_{Ed}}{f_y} = 0.5202 \quad (32)$$

$$\sigma_{Edmax} = 0.53 \quad (33)$$

Analysis and assessment of material usability

The dimension of the thickest element was the following:

$$t_{max} = 20.5 \text{ mm} \quad (34)$$

The lowest possible temperature of the thickest element was the following:

$$T_{ED} = -37\ °\text{C} \quad (35)$$

Presented below are the data from Table 2.1, contained in the PN-EN 1993-10 standard [7]. The greatest permissible material thickness in relation to an effort of 0.75 and a temperature of – 40 °C was the following:

$$t_{\sigma Ed75} = 15 \text{ mm} \quad (36)$$

The greatest permissible material thickness in relation to an effort of 0.50 and a temperature of – 40 °C was the following:

$$t_{\sigma Ed50} = 25 \text{ mm} \quad (37)$$

The greatest permissible thickness of the material in relation to an effort of 0.53 is presented below. The parameters of the model were determined using the Veusz programme:

$$t_{\sigma Ed53} = 39.9\sigma_{Edmax} + 44.9 \quad (36)$$

$$t_{\sigma Ed53} = 23.7 \text{ mm} \quad (39)$$

The value specified in (39) indicates that, under the conditions assumed for the analysis, the maximum thickness of the structural element could be greater than the thickest part of the sections in the node under consideration. Therefore, the qualitative selection of steel could be based on the PN-EN 1993-10 standard [7].

4. Summary

The above-presented possibilities of assessing various structural elements in terms of brittle fracture indicate many available solutions which could be used at the stage of design, production or operation. It is important to properly assess the resistance to brittle fracture in each of the presented cases as well as to estimate the temperature in relation to which impact energy amounts to 27 J. This is necessary both as regards the application of harmonised standards and the SINTAP/FITNET procedures (for which, due to the volume of the work, the relevant formulas and auxiliary tables have not been provided). The inclusion of fracture mechanics in the assessment of brittle fracture of pressure equipment or construction products is necessary, particularly when one wants to avoid applying conservative material data at the design stage and ensure the safe use in the event of the detection or assumed presence of a hypothetical fracture (which could be demonstrated using analysis in accordance with FAD diagrams).

REFERENCES

[1] Gałkiewicz J.: Charakterystyka modułu „Zmęczenie Elementów Konstrukcyjnych" zawartego w procedurach FITNET, V Międzynarodowe Sympozjum Mechaniki Zniszczenia Materiałów i Konstrukcji, Augustów 2009.
[2] Gałkiewicz J., Graba M.: Procedury FITNET – nowa metoda oceny wytrzymałości elementów konstrukcyjnych, XI Krajowa Konferencja Mechaniki Pękania, Kielce/Cedzyna 2007.
[3] Giżejowski M., Ziółko J.: Budownictwo Ogólne. Tom 5. Stalowe konstrukcje budynków. Projektowanie według Eurokodów z przykładami obliczeń, Arkady, Warszawa 2010.
[4] Graba M.: Praktyczne zastosowanie procedur FITNET – moduł mechaniki pękania i zmęczenia materiału, V Międzynarodowe Sympozjum Mechaniki Zniszczenia Materiałów i Konstrukcji, Augustów 2009.
[5] Neimitz A., Dzioba I., Graba M., Okrajni J.: Ocena wytrzymałości, trwałości i bezpieczeństwa pracy elementów konstrukcyjnych zawierających defekty, Wydawnictwo Politechniki Świętokrzyskiej, Kielce 2008.
[6] Sedlacek G.: Commentary and worked examples to EN 1993-1-10 "Material toughness and through thickness properties" and other toughness oriented rules in EN 1993, European Commission, Joint Research Centre, Aachen 2008.
[7] Norma PN-EN 1993-10. Eurokod 3: Projektowanie konstrukcji stalowych – Część 1-10: Dobór stali ze względu na odporność stali na kruche pękanie i ciągliwość międzywarstwową, 2007.
[8] Norma PN-EN 1993-12. Eurokod 3. Projektowanie konstrukcji stalowych – Część 1-12: Reguły dodatkowe rozszerzające zakres stosowania EN 1993 o gatunki stali wysokiej wytrzymałości do S 700 włącznie, 2008.
[9] Norma PN-EN 10025-1. Wyroby walcowane na gorąco ze stali konstrukcyjnych – Część 1: Ogólne warunki techniczne dostawy, 2007.
[10] Norma, PN-EN 10025-2. Wyroby walcowane na gorąco ze stali konstrukcyjnych – Część 2: Warunki techniczne dostawy stali konstrukcyjnych niestopowych, 2019.
[11] Katalog ArcelorMittal, Kształtowniki i pręty walcowane na gorąco, 2011.
[12] Procedury FITNET, Procedury FITNET, 2006.
[13] Rozporządzenie, Rozporządzenie Parlamentu Europejskiego i Radu Unii Europejskiej nr 305/2011 z dnia 9 marca 2011 r. ustanawiające zharmonizowane warunki wprowadzania do obrotu wyrobów budowlanych i uchylające dyrektywę Rady 89/106/EWG, Dziennik Urządowy Unii Europejskiej, Bruksela, 2011.