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THE FIRE RESISTANCE OF STEEL PLATE GIRDERS WITH SLENDER WEBS
– A COMPARATIVE STUDY

ODPORNOŚĆ OGNIOWA STALOWYCH BLACHOWNIC Z CIENKOŚCIENNYMI
ŚRODNIKAMI – STUDIUM PORÓWNAWCZE

Abstract

A comparative study of the load-bearing capacity of selected steel plate girders with slender webs under fire action is presented in this paper. Typical plate girders and girders with corrugated webs are considered. Stiffeners are only placed at the ends of cantilever beams so the shear buckling is a possibility. Fire resistance of the analysed members was estimated using two separate FEM software packages. Moreover, the computational approach applied for each case was different, thus validation of the software was possible. Failure modes, critical temperatures and deformations for steel plate girders subject to fire temperatures are also presented.

Keywords: fire resistance, steel plate girder, corrugated webs, local buckling

Streszczenie

W artykule przedstawiono studium porównawcze nośności wybranych blachownic stalowych ze smukłym środkiem poddanych oddziaływaniom pożarowym. W analizie uwzględniono typowe blachownice oraz blachownice z falistym środkiem. Żebra umieszczono tylko na końcach wspornika, w związku z czym możliwa była utrata stateczności przy ścinaniu. Odporność pożarową analizowanych elementów oszacowano za pomocą dwóch niezależnych pakietów oprogramowania bazujących na metodzie elementów skończonych. Co więcej, podejście obliczeniowe zastosowane w obu przypadkach było różne, w związku z czym możliwa była walidacja użytych pakietów oprogramowania. Zaprezentowano również modele zniszczenia, temperatury krytyczne oraz deformacje dla blachownic stalowych poddanych działaniu temperatury pożarowej.

Słowa kluczowe: odporność pożarowa, blachownica stalowa, środki z blachy profilowanej, utrata stateczności miejscowej

1. Introduction

The development of lightweight steel structures and the current trend to use thin-walled members allows obtaining reductions in both material consumption and the overall costs of construction projects; however, their use demands a more thorough knowledge of the behaviour of structures in the event of fire.

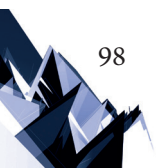
Experimental research is without any doubt the best way to evaluate the performance of a structure during conditions of elevated temperature resulting from fire. However, this is too inconvenient and expensive to be commonly used. Instead, in normal practice, a set of design rules are recommended for the purpose; these may also be aided by computer technology. Numerical simulations with validated programmes can be used to check the accuracy of measured dimensions and/or observe the behaviour of a structure in conditions of fire.

Design rules given in the current standard EN 1993-1-2 [4] for the 4th class of cross sections are limited to a certain range of temperatures. According to the standard for this type of cross section, the critical temperature is always 350°C and the standard does not, for example, consider the degree of utilization of selected parts of the steel member. Such an approach seems to be conservative. Even taking into account data that could be found in [7] (i.e. some additional verifications of fire resistance that are not covered by [4]) the assessment of the load-bearing capacity of steel plate beams or columns with slender webs is still not fully recognised in conditions of elevated temperature. To investigate this situation, extended research has been recently performed in a few European countries. Some of the most important results in this field have been obtained for shear buckling [14, p. 34–43] and lateral-torsional buckling [2, p. 410–421], [13, p. 2–18]. The outcomes of experimental investigations concerning the behaviour of columns are presented in [5] while outcomes for research on beams with corrugated webs are provided in [12, p. 69–78]. Generally, in almost all the previously mentioned papers, computer simulations have been validated by full-scale tests. This approach seems to be the most appropriate in order to obtain high-quality results of computer simulations, but it is also quite expensive and time-consuming. Another fairly common way how to validate computer calculations is to use at least two numerical methods based on different theoretical foundations (e.g. theories of plastic flow etc.) and obtain similar effects [1, p. 83–142]. In this paper such approach is presented. The two advanced software packages SAFIR [6, p. 300–323] and ABAQUS [9] are used here for this purpose.

2. Comparative study

2.1. COMPUTER SIMULATIONS PERFORMED USING THE ABAQUS PROGRAM

Three different cantilever beams were considered. One was a typical steel plate girder with flanges measuring 250 mm wide and 20 mm thick, a web measuring 750 mm high and 5 mm thick. The two other beams were steel plate girders with corrugated webs (SIN type) marked as WTA750 and WTC750. Their flange dimensions were the same as for the plate beam but



the thicknesses of the webs were 2 mm and 3 mm, respectively. Each beam was 3.1 m long and the live load at the end of the cantilever is 25 kN. The flanges were made of S235JRG2 steel grade with a yield strength of $f_y = 240$ MPa and webs were made of S235JR with a yield strength of $f_y = 215$ MPa. The stress-strain relationship and reduction factors were exactly the same as those given by EN 1993-1-2 [4]. The beams were modelled with the use of shell elements (S4R5) which are 4 node elements with 5 degrees of freedom in each node. The web depth in the case of the SIN profiles was divided into 16 elements, which gives 3,008 elements in total for the whole beam. For the plate girder, these values are 26 and 4,784, respectively. The view of a model prepared using ABAQUS software [9] is presented in Fig. 1. The cross section was heated according to the natural fire curve shown in Fig. 2. For simplicity, it was assumed that temperature of the web was always equal to the gas temperature, while the temperature of the flanges was calculated according to EN 1993-1-2.

In order to estimate the load-bearing capacity of a cantilever beam under fire action, the Riks method is used. This approach is valid for the unstable, geometrically nonlinear collapse of structures. The nonlinear properties of materials are also taken into consideration. The described method consists of several successive steps that form the analysis as a whole. For each step, all the steel properties are determined for the given temperature and only the load parameter is raised. If the obtained load is higher than the required 25 kN, the simulation goes to the next step and is repeated once again using reduced properties of steel for the next higher temperature value. Otherwise, when the required load ($P = 25$ kN) cannot be reached, the simulation stops and the fire resistance is taken as the value for the last fully completed step. All calculations presented in this paper were performed in [15].

The described methodology does have some disadvantages. For example, during a typical fire episode, it is usual for the dead and live loads to have been added to the structure before the rise of the temperature took place. In the result some parts of strains caused by mechanical loads are developed at ambient temperature. Moreover, following increase of strains during a fire should be calculated using steel properties that depends on elevated values of temperature. However, as previously mentioned, for comparison reasons, the material properties for separate simulations are constant and the force parameter is increased. The other significant disadvantage here is the computational cost of the simulation which must be performed many times before the final estimation of fire resistance is obtained.

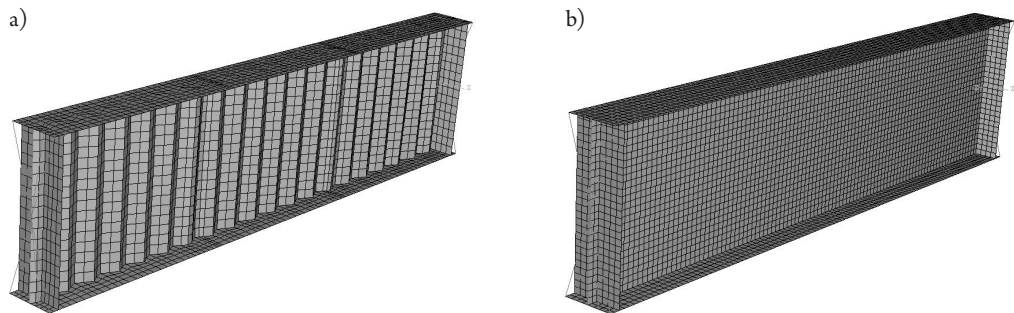


Fig. 1. Analysed models prepared using Abaqus software: a) SIN profiles; b) plate girder

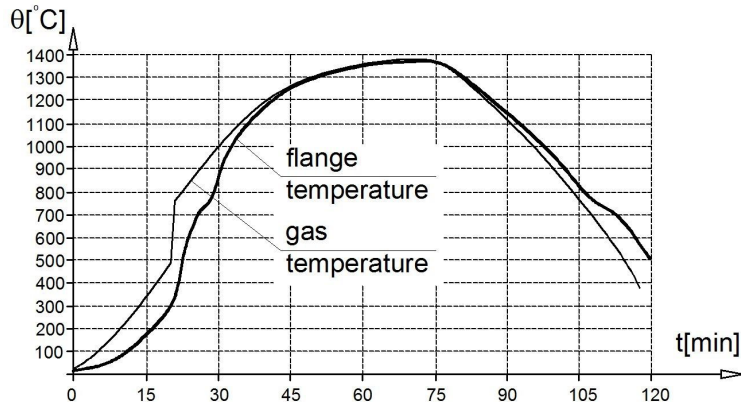


Fig. 2. Temperature during the considered natural fire

2.2. Computer simulations performed using the Safir program

The same beams analysed with Abaqus were analysed again using the Safir software program [6, p. 300-323]. As before, the steel properties and reduction factors were taken from EN 1993-1-2; however, the method used for conducting the analysis was quite different. Firstly, a dynamic approach was applied to overcome local instabilities. The mass matrix was included explicitly, while the damping matrix was introduced as so-called 'numerical damping' and Newmark's method was used to solve the governing equation. The time step for the analysis was automatically selected by the program and the come back factor was 0.0001 sec. The shell elements are quadrangles based on four nodes, each bearing three translations and three rotations. A relatively fine mesh was set in the model with an element size of around 25 x 25 mm, which gave a total of 7,072 elements for the plate girder. The load achieved from the last converged step of the Abaqus analysis was taken into account so the load values were 40.76 kN for the plate girder, 26.44 kN for the WTC type and 24.1 kN for the WTA girder type. Recommended biaxial plane stress material type STEELEC32D was applied in the simulations.

As the used software package is specified for simulations of a structure's behaviour under fire action, it has some further features that should be mentioned here. This especially applies to the fact that, unlike the previous case, the temperature is calculated numerically across the section. As a result, the temperature varies along the thickness of the steel plate and this may lead to additional stresses. Moreover, dead and live loads were added to the structure during the first twenty seconds of analysis and only after this period did the temperature significantly increase. One can notice that this approach is much closer to the real behaviour of structures in conditions of fire than the method adopted for the previously described Abaqus simulations. Models created with the use of Safir software are presented in Fig. 3. More details regarding the exact properties and limitations of the software can be found in [6, p. 300-323] and [7].

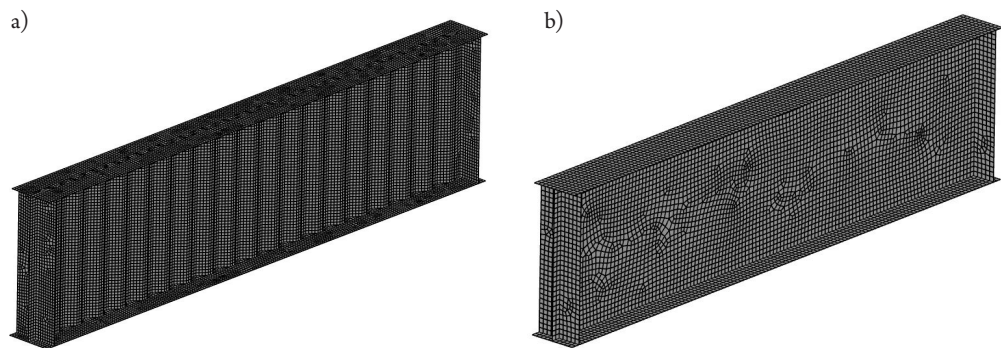


Fig. 3. Analysed models prepared using Safr software: a) SIN profiles; b) plate girder

2.3. Results of the analyses

The main results obtained for the both described calculation methods are: fire resistance – expressed by the time after which the collapse of the beam occurs; critical temperature of the web and the flanges; final deflections; types of failure modes. A comparison of these results is presented in Table 1 for the steel plate girder, in Table 2 for the WTA SIN type girder and in Table 3 for the WTC SIN type girder.

Table 1. Results – steel plate girder

	Critical temperature – flange [°C]	Critical temperature – web [°C]	Maximum deflection [mm]	Fire resistance [min]
SAFIR	640	800	16	24
ABAQUS	656	848	12.5	25

Table 2. Results – SIN WTA type girder

	Critical temperature – flange [°C]	Critical temperature – web [°C]	Maximum deflection [mm]	Fire resistance [min]
SAFIR	590	746	83	23
ABAQUS	450	771	10	22

Table 3. Results – SIN WTC type girder

	Critical temperature – flange [°C]	Critical temperature – web [°C]	Maximum deflection [mm]	Fire resistance [min]
SAFIR	670	815	96	24.5
ABAQUS	627	835	10	24.5

It is clearly shown that for all the simulations, nearly no differences in the predicted fire resistance occurred. However, it should be stressed once more that the estimated collapse time for the same tests using the ISO curve [3] might lead to significantly lower results. For the plate girder and the SIN WTC type girder, the critical temperatures of the web and flanges given by both software programs are practically the same. The highest disagreement is as much as 10%. This is not the case for the flange of the WTA girder. However, this outcome can be easily justified when we look at the time-temperature relationship presented in Fig. 2. The failure occurs at the same time when a flashover takes place (vertical part of the gas temperature graph somewhere around $t = 22.5$ min) so the changes of the temperature are very high over an extremely short period of time. Therefore, even a small difference in the heating calculation method, which is obvious according to the previously described facts (see clauses 2.1 and 2.2), leads to inaccuracy in the estimation of flange temperature. This is not that visible for the web because of its thickness – for such a plate, its temperature is always almost equal to the temperature of the fire environment regardless of the calculation methodology.

The deflections obtained using the Safir software are higher than those obtained for the Abaqus simulations – this is due to using the dynamics approach in Safir. The Riks method stops immediately when some instability is detected while the dynamics approach can overcome this point and calculations are continued for some additional time. However, the analysed structure is statically determinate, therefore the only advantage of the dynamic approach is a better insight into the beam's post-buckling behaviour. For indeterminate structures where redistribution of forces appears and the impact on fire resistance may be crucial, a dynamic approach in the incremental analysis is recommended.

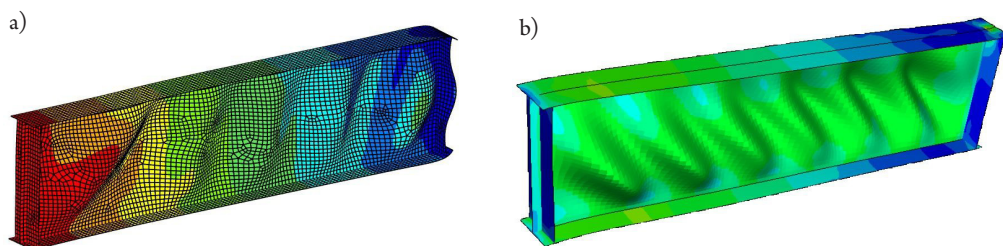


Fig. 4. Failure modes for steel plate girder: a) Safir software (fixed support on the right side of the beam); b) Abaqus software (fixed support on the left side of the beam)

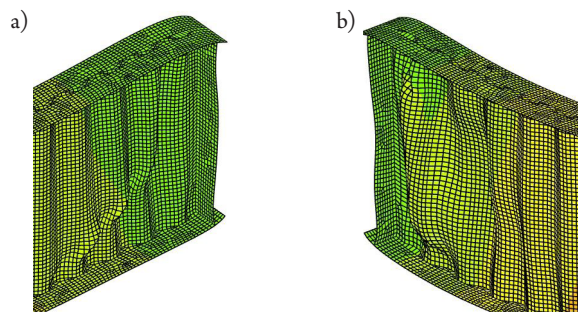


Fig. 5. Failure modes near the support obtained using Safir software for: a) SIN WTA girder; b) SIN WTC girder

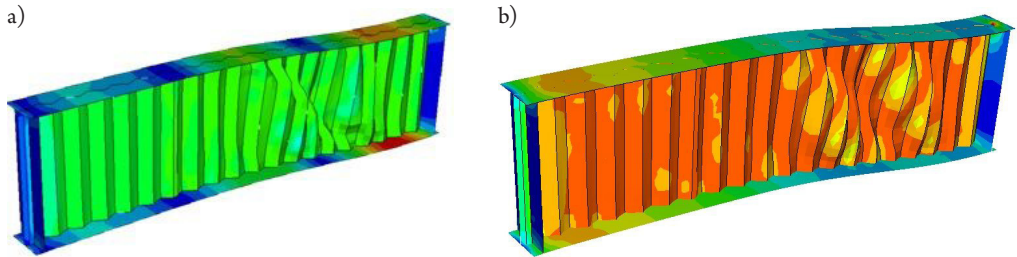


Fig. 6. Failure modes obtained with Abaqus software (fixed support on the left end of the beam) for: a) SIN WTA girder; b) SIN WTC girder

The failure modes for the girders are presented in Figs. 4-6. Once again, results for the plate girder are very close to each other. Firstly buckling appears for the web due to compression developed by temperature differences between the web and the flanges. However, this deformation does not affect the load-bearing capacity of the whole beam. The structure remains stable until the web buckling near the support occurs. This phenomenon is more visible for the model created using Safir software (Fig. 4a). Furthermore, the observed shape of deformations is quite similar to those observed in the steel structures after the real fire (see Fig. 7 [8, p. 51-66]).

The failure modes obtained for the SIN type profiles are more varied. In the case of the Abaqus software, web destruction occurs near the middle of the span. This cannot be easily explained and further investigation is required here. The form of web buckling presented in Fig. 5 (and especially in Fig. 5b) should be recognised as the correct one. Firstly, it appears near the support where the bending and shear forces reach maximum values. Secondly, this type of web buckling is similar to the results of experimental research obtained by Kuchta [10] for ambient temperatures (Fig. 8).



Fig. 7. Deformations of steel beams after real fire exposure [8, p. 51-66]



Fig. 8. Failure mode for the SIN type profile according to [10]

3. Conclusions

The comparison of computer simulations performed for different types of steel girders affected by fire action was analysed. Two separate approaches to the calculations and two separate software programs were used to estimate the fire resistance of cantilever beams and to validate the computational software. The results obtained for a steel plate girder are satisfactory and both software programs predict very similar data with regard to time when the failure occurs, deflections and failure modes.

A few more significant differences for SIN type profiles can be observed; however, most of these were expected and can be easily explained. Moreover, it is clearly shown that the load-bearing capacity of 4th class cross sections cannot be limited to the critical temperature of 350°C (15 minutes) and simple fire unprotected structures could survive nearly 25 minutes of natural fire. Similar conclusions for other types of steel members have also been drawn by other researches e.g. [11, p. 370–382].

References

- [1] Arbocz J., *Post-buckling behaviour of structures. Numerical techniques for more complicated structures*, Buckling and Post-Buckling. Lecture Notes in Physics, Vol. 288. Springer-Verlag, Berlin, Heidelberg, 1987, 83–142.
- [2] Couto C., Vila Real P., Lopes N., Zhao B., *Numerical investigation of the lateral-torsional buckling of beams with slender cross sections for the case of fire*, Engineering Structures, Vol. 106, 2015, 410–421.
- [3] European Committee for Standardization, *EN 1991-1-2: Eurocode 1: Actions on structures. Part 1–2: General actions - Actions on structures exposed to fire*, Brussels, Belgium 2002.
- [4] European Committee for Standardization, *EN 1993-1-2: Eurocode 3: Design of steel structures. Part 1–2: Structural fire design*, Brussels, Belgium 2005.
- [5] Franssen J.-M., Fohn T., *FIDSEC4: Fire behaviour of steel members with class 4 cross sections under axial compression and axial compression with eccentricity*, Report of the experimental tests performed at the University of Liege, 2013.
- [6] Franssen J.-M., Gernay T., *Modelling structures in fire with SAFIR: Theoretical background and capabilities*, Journal of Structural fire Engineering, Vol. 8 issue 3, 2017, 300–323.
- [7] Franssen J.-M., Vila Real P., *Fire design of steel structures 2nd edition*, ECCS Press and Ernst & Sohn Wiley Company, 2015.
- [8] Gwóźdź M., Woźniczka P., Tkaczyk A., *The reconstruction of fire-damaged industrial steel halls*, Safety&Fire Technique, Vol. 44, Issue 4, 2016, 51–66.
- [9] Hibbit, Karlsson & Sorensen Inc., *Abaqus: Analysis user's manual*, Volumes I–IV, version 6.10, 2010.
- [10] Kuchta K., *Nośność i sztywność blachownic o falistych środkach*, Politechnika Krakowska, 2004. Rozprawa doktorska.
- [11] Maia E., Couto C., Vila Real P., *Critical temperatures of class 4 cross-sections*, Journal of Constructional Steel Research, Vol. 121, 2016, 370–382.
- [12] Maślak M., Łukacz M., *Interactive shear resistance of corrugated web in steel beam exposed to fire*, Journal of Structural Fire Engineering, Vol. 7, Issue 1, 69–78.
- [13] Prachar M., Hricak J., Jandera M., Wald F., Zhao B., *Experiments of class 4 open section beams at elevated temperature*, Thin-Walled Structures, Vol. 98, 2016, 2–18.
- [14] Reis A., Lopes N., Vila Real P. *Shear-bending interaction in steel plate girders subjected to elevated temperatures*, Thin-Walled Structures, Vol. 104, 2016, 34–43.
- [15] Tatara Z., *Design of workshop hall (24 x 42 m) with crane transportation. The influence of thermal load on carrying-capacity of chosen steel members*. Brandenburg Technical University Cottbus, Cracow University of Technology, Diploma Work, 2006.