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DISCUSSION ON A SYSTEMATIC APPROACH TO VALIDATION OF SOFTWARE FOR STRUCTURES IN FIRE

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ABSTRACT

A validation exercise has been performed for the thermo-mechanical software SAFIR® based on a dual approach. First, the examples proposed in the German National Annex of EN 1992-1-2 have been calculated with SAFIR and, second, the references to SAFIR found in scientific publications have been analysed with respect to the level of accuracy estimated by the authors for the results of SAFIR. The aim of this paper is not to present the detailed results of this validation exercise (which are published in open access reports). The focus is more on a critical analysis of the examples presented in the German National Annex which indeed paved the way to a systematic approach to validation of SiF software but could be improved, namely by including sensitivity analyses on the discretisation, a better description of some input data particularly in the material models, a presentation of the means used to obtain some reference results and a clear definition of the failure criteria to be used for determining fire resistance times. Furthermore, extensive analysis of the literature showed that the wide field of application of a typical SiF software requires an extension of the domain covered by the standard on concrete structures.

Keywords: Structures, finite element modelling, benchmarking, validation, fire tests

1 INTRODUCTION

Numerical models are used more and more in structural fire engineering. This trend is supported by extensive research efforts toward the development of computational models. However, it has to be recognised that, compared to CFD software, the validation of advanced tools for the thermo-mechanical analysis of structures in fire has received little attention, which may be partly due to a lack of clear guidelines and standards. Some efforts have been undertaken ([2], [12]), but systematic validations of software used in the field remain the exception rather than the norm. Validation of structural fire analysis codes can rely on benchmarking examples such as those provided in the German National Annex of EN 1992-1-2 [1], which has attracted the attention of the authors and will be commented in this paper. On the other hand, confidence in numerical models may rely on their validation against experimental tests, but to infer validity from such comparisons, a statistically relevant database of tests should be considered, which is rarely the case.

This paper describes a systematic approach for software validation based on a combination of standard benchmarking examples and literature tests review. The work, applied to the particular software SAFIR® [3] but valid in general, aims to:

1. Critically discuss the numerical modelling of the DIN benchmarking examples, while proposing relevant sensitivity analyses;

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2. Present a meta-analysis review of published tests modelled with a well-established software. This review also allows identifying gaps between the DIN benchmarking examples and common numerical modelling applications.

2 VALIDATION THROUGH BECHMARKING CASES

2.1 German National Annex to the Eurocode

Annex CC of DIN EN 1992-1-2 NA (here referred as "DIN") [1] presents a series of cases that allow benchmarking software tools aimed at the design of concrete structures in a fire situation. The validation typically consists in a comparison between the value of a result (e.g. temperature, or displacement) obtained by the tool under validation and the value given as a reference and supposed to be the *true* result. The value obtained must fall within an interval stipulated by the document.
The eleven examples present in DIN are based on a research project conducted by Hosser et al [4]. The seven first cases aim at checking specific calculations, for which results are expected to be matched with a great accuracy by the tool being tested. Some of these tests are simple "Unity tests". That means a specific test built up to verify good coding of a specific function. This is the case, for example, of Example 4 about thermal expansion of a simple unloaded bar. Ideally, code developers should develop their own unity tests for every function involved in the code. The four last cases aim at checking the entire calculation process, for which results are expected to be close to the ones obtained from specific software (namely Ansys and STABA-F) that are described in [5] as "*approved programs*".
All the examples in the DIN were modelled using SAFIR. A detailed description of these analyses can be found in [6]. Table 1 shows a short description of the examples and the results of the comparison between the values obtained by SAFIR and the reference values prescribed in DIN.

Table 1. Summary of results obtained with SAFIR for the collection of examples in DIN.

Example	Test criterion	Check on	Limits respected
1	Heat transfer (cooling)	Specific function	Yes
2	Heat transfer (heating)	Specific function	Yes
3	Heat transfer through several layers	Specific function	Yes
4	Thermal expansion	Specific function	Yes
5	Temperature-dependent stress-strain curves of concrete and steel	Specific function	Yes
6	Temperature-dependent limit-load-bearing capacity of concrete and steel	Specific function	Yes
7	Development of restraint stresses	Specific function	Yes
8	Weakly reinforced concrete beam	Full calculation process	Yes
9	Heavily reinforced concrete beam	Full calculation process	Yes*
10	Reinforced concrete column	Full calculation process	Yes*
11	Composite column with concrete cores	Full calculation process	Not all

* values are within limits depending on the assumptions considered

2.2 Sensitivity analyses

DIN gives reference values to be obtained by the simulation, with some tolerance, but it does not address at all the questions of discretization in time or in space, which can significantly affect the accuracy and quality of the results. A tool that can meet the requirements only with an extremely fine mesh and an extremely short time step may yield unrealistic results with more practical meshes and time steps. It is of uttermost importance to know how the quality of the results is affected when the discretisation is degraded. Only by testing different refinements and configurations of the mesh, different time steps and other parameters, is it possible to learn how a tool responds and to prove that results are consistent when enough detail is used in the models. Therefore, extensive sensitivity analyses have been conducted in the validation process of SAFIR through the DIN benchmarking cases [6]. As an example, Fig. 1 shows part of a sensitivity analysis made for Example 1.

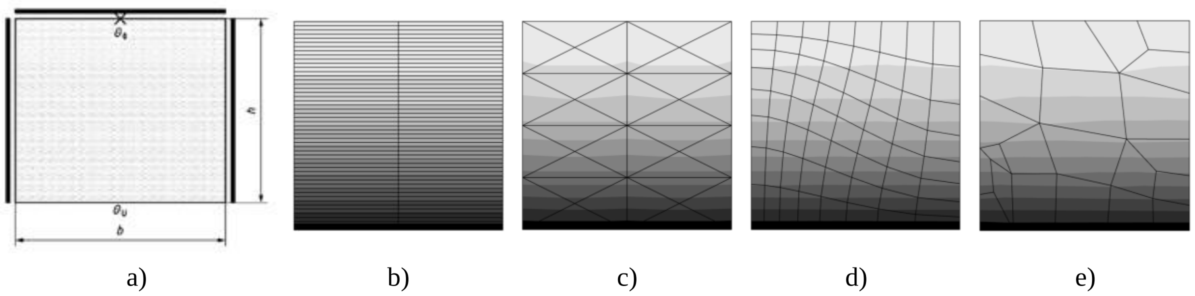


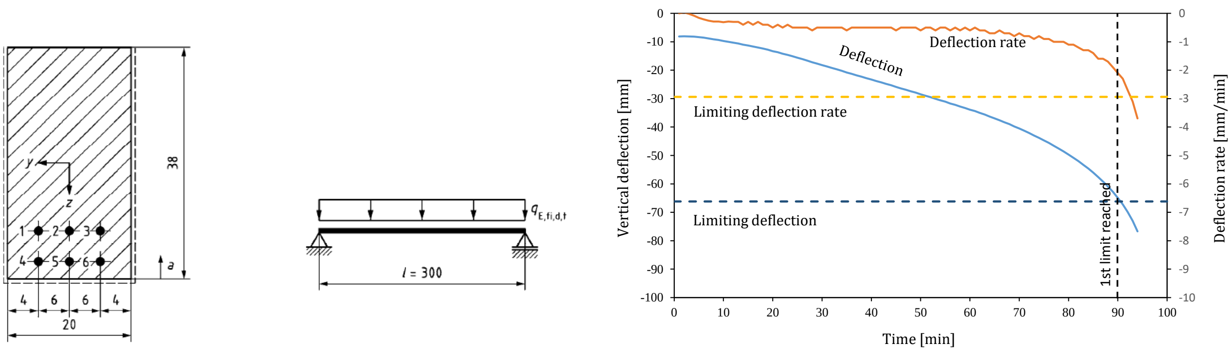
Fig. 1. Part of a sensitivity analysis performed with SAFIR® for Example 1 in DIN (temperatures plotted): a) section tested; b) mesh with rectangles; c) mesh with triangles; d) distorted mesh; e) unstructured mesh

The analysis allowed quantifying how the solution converges to the theoretical solution when the density of the mesh is increased and the value of the time step is reduced. Additional conclusions drawn in [6] state that, when refining the mesh:

- Rectangular elements converge slightly faster than triangular elements.
- Structured meshes are more efficient.
- Slight differences are observed in distorted structured meshes but those are still efficient;
- Unstructured meshes are less efficient but still lie in the acceptable range of the standard.

2.3 Sources of discrepancies in results

The results of SAFIR for the last three examples present issues with regards to the limits stipulated by the DIN. For Example 9, the goal is to determine the area of steel A_s that makes the beam resist exactly 90min under standard ISO fire. If one considers the last converged time step of the simulation as the time of failure, the determined A_s will fall outside the boundaries establish by the DIN. However, if the failure criteria described in EN1363-1 [7] is applied, the time of failure is shorter than the last converged time step (see Fig. 2) and the results fall within the limits. Even in a prescriptive framework, ambiguities in the definition of the failure criteria can influence the fire resistance rating as shown in [13]. Therefore, a clear definition of failure, and the criteria used to determine the failure time, should be specified in the DIN as being on the basis of the results.



a) cross-section and beam configuration b) deflection and deflection rate vs. time

Fig. 2. Geometry and configuration of the beam and deflection and deflection rate vs. time, with A_s = 8.84cm² for Example 9 in DIN, with limits for the load bearing capacity according to the criteria in EN1363-1 [7]

Another question that can be raised is that, despite being referred to as "*approved tools*" in [5], there is no unquestionable proof of the accuracy of these tools that have been granted some sort of *grandfather's right*. There is also no indication on the assumptions made in the analyses that produced the reference results. For instance, it is not explicitly mentioned in this Annex CC of DIN what should be the values used for the thermal conductivity or the moisture content in concrete.

Additionally, it is noted that 3 other tools developed independently, namely InfoGraph [8], FRILO [9] and mbAEC [10], yield identical results to those obtained with SAFIR for the considered DIN examples. This fact is certainly something that should not be neglected and that contributes to the uncertainty on how the results taken as reference in DIN were determined and on their accuracy.

3 META-ANALYSIS OF PUBLISHED TEST MODELS

3.1 Research methodology

The goal of this meta-analysis is to assess the suitability of SAFIR to model practical and full-scale problems of engineering, based on the accuracy of predictions of the temperature distributions in real structures subjected to fire and fire resistance times as well as a correct prediction of the structural behaviour. The approach consisted in reviewing the scientific documents that have cited SAFIR throughout the years, and extracting from these documents any published comparisons between SAFIR results and results from experimental tests and/or results obtained with other software. Results were then compiled in a list that has been made available online [11].

Only documents written in English were considered. These constitute the major part of the documents found during this research, with only a very minor part being written in other languages.

3.2 Documents

As of March 2018, 551 documents with a reference to SAFIR have been found. From these, 411 have calculations performed by SAFIR, 108 have only a reference to SAFIR, and it was not possible to check the content of the remaining 32 documents, because they are not available online and could not be obtained by any of the methods used.

Most of the documents found (about 90 %) are either journal articles or conference papers. Only these were further considered. This is justified by the fact that usually the results of the same calculations made in PhD thesis or books are also published in articles and papers, and that MSc thesis and technical reports do not necessarily have a sufficiently reliable cross checking of results that justify their inclusion in such an analysis.

Fig. 3 shows the 134 documents containing comparisons between SAFIR and the two types of sources of results: experimental tests and other advanced calculation models.

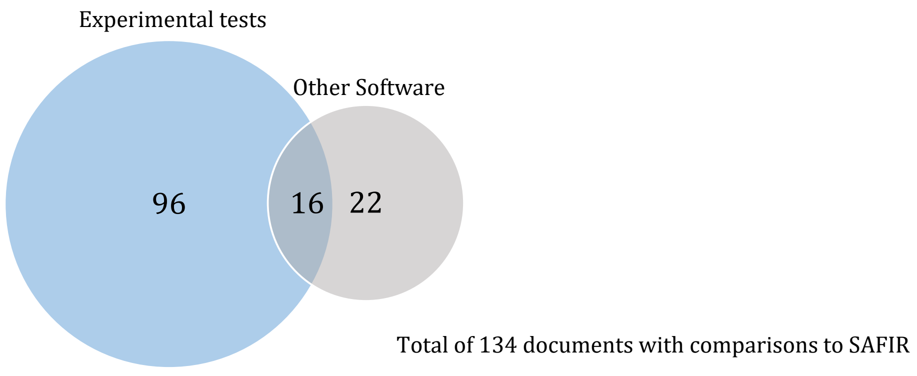


Fig. 3. Number of journal articles and conference papers with comparisons of SAFIR to experimental tests, to other software, and to both.

3.3 Classification

A classification was made by quantifying the number of documents for the different structural elements and materials used, the kinds of phenomenon, property or behaviour analysed, the types of finite elements used in the model, and the fire curves applied. The results are depicted in Fig. 4.

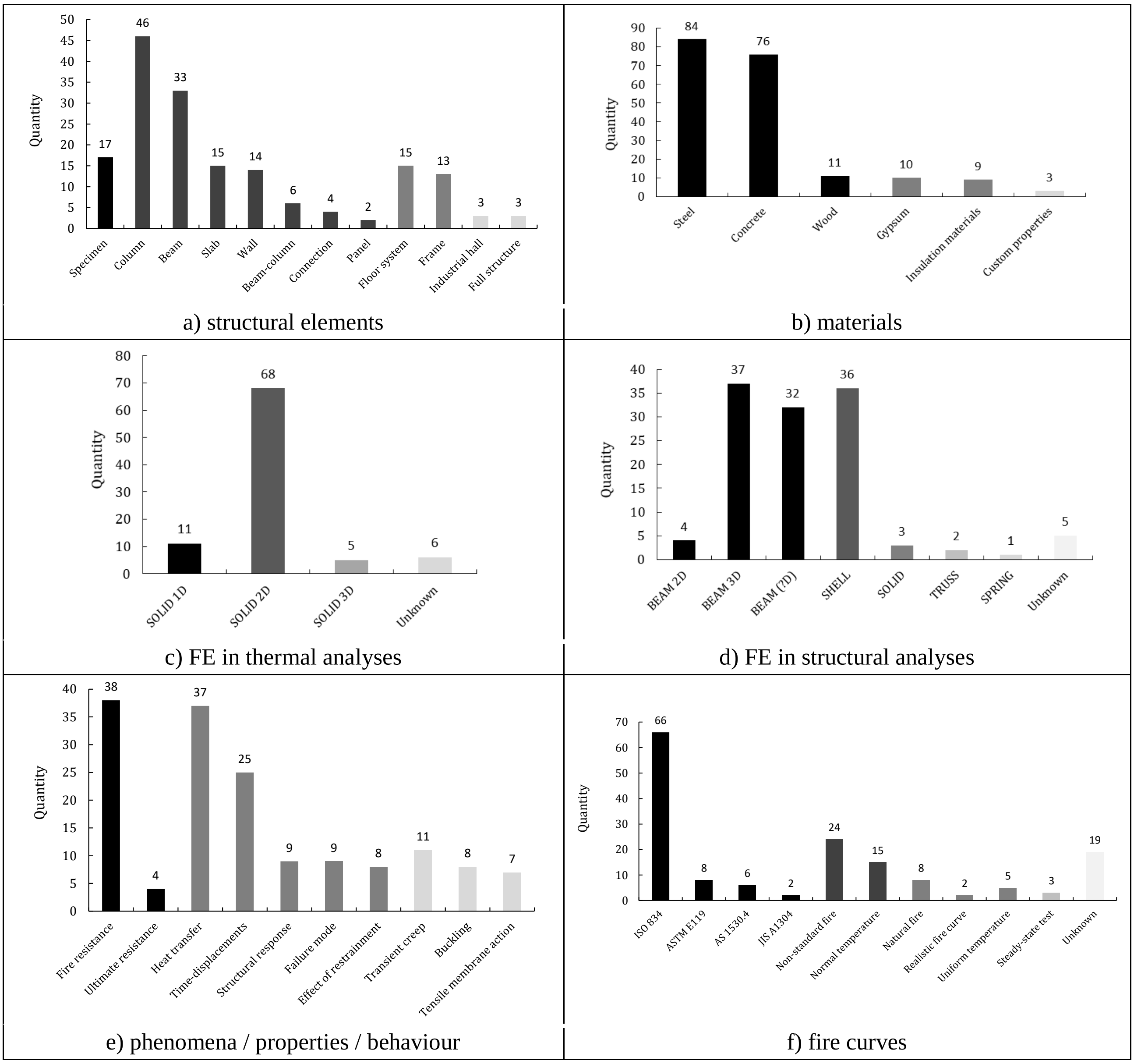


Fig. 4. Classification of journal articles and conference papers presenting comparisons between SAFIR and experimental tests or other software, according to different aspects

Based on Fig. 4, the following conclusions are drawn:

- Most analyses are done for isolated members, especially columns, beams, slabs and walls.
- Steel and concrete are by far the two materials most used in the comparisons.
- SOLID 2D, in thermal analyses, and BEAM (2D and 3D) are clearly the FE most extensively covered, while SHELL are also commonly used.
- Fire resistance, time-displacements and heat-transfer are the most studied subjects.
- A large part of the analyses use the Standard ISO834 fire curve, whereas an also significant amount of analyses are done with non-standard fires and at normal temperature.

3.4 Comparisons

An attempt at a qualitative analysis that may easily provide an overall picture of the results was made, and the comments done by the authors of the analyses were reviewed, so that they may provide some insights on the results of the comparisons.

3.4.1 Level of agreement

The level of agreement between results from SAFIR and other sources of results was qualitatively classified according to a scale that went from 'very poor' to 'very good'. As with any other qualitative evaluation, the interpretation of the published results and comments involved some level of subjectivity. Nevertheless, the objective was to match the typical keywords used by the authors of the analyses, such as "very good" and "quite satisfactory", with the scale previously mentioned. Fig. 5 shows the distribution of the documents according to the different levels of agreement:

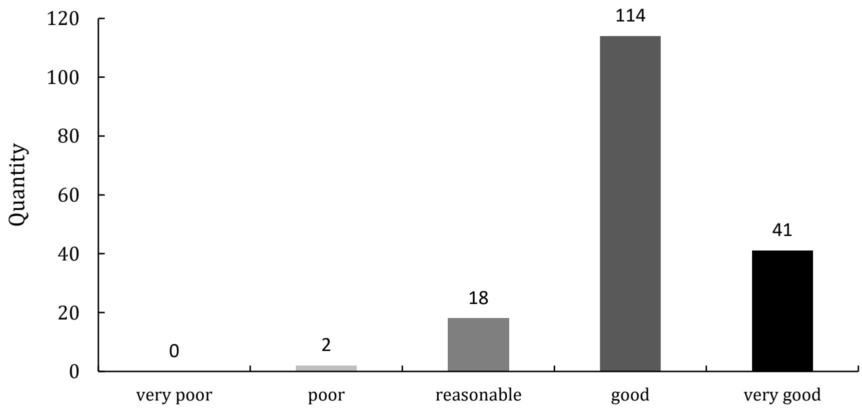


Fig. 5. Classification of scientific publications presenting comparisons between SAFIR and experimental tests or other software, as a function of the level of agreement.

3.4.2 Review of comments

Based on the comments extracted from the considered 134 publications, the main conclusions indicated by authors on their comparisons to SAFIR are, as regards the capabilities of SAFIR:

- Temperature distributions throughout time are generally well predicted.
- Good agreement is generally obtained for fire resistance times, ultimate loads and time-displacements.
- Forces generated by loads and resulting from restrained thermal expansion are well predicted.
- Failure modes and buckling shapes are well captured in steel structures. Residual stresses, when considered, are correctly taken in account.

However, the following limitations of SAFIR are noted:

- Water movement within concrete is not simulated, which may result in slight over-predictions of temperature.
- Spalling is not accounted for, which can result in over-predictions of the resistance of RC structures.
- BEAM elements do not capture shear deformation and can lead to over-estimations of resistance whenever shear is the main failure mode.

4 DISCUSSION

4.1 Benchmarking

Benchmarking examples should include sensitivity analyses that can provide proof that results converge as more refined models and shorter time steps are considered. Other analyses may include the study of the influence of the different types of analysis or solvers (static, dynamic, implicit, explicit, etc.). Detailed description of the inputs of the models is required, as well as an explicit definition of the “failure” criteria used to define the fire resistance time.

As such information is missing in some of the examples of the DIN, the authors consider that the excessive deviation observed for some of the Examples does not invalidate the ability of SAFIR to model the behaviour of concrete beams subjected to fire.

Although the DIN document was a major step in the good direction, it is clear that the comprehensive benchmarking of an advanced SiF software with a wide field of application requires addressing a broader range. Benchmark examples should be developed namely in:

- timber structures;
- structures with shell elements, such as concrete walls and slabs or slender steel structures where local buckling may develop;
- full structures or substructures with load redistribution.

The amplitude of the task is such that it cannot be undertaken at a national level.

4.2 Meta-analysis

The meta-analysis on the typology and quality of the comparisons that have been made in the literature between SAFIR and tests or other advanced tools offers valuable information.

Most of the comparisons have been done on single structural members. This is justified by the fact that it is harder to have access to tests on complete structures. However, it is important that at least some comparisons of results for these full structures are done with the software being tested (if not against experimental tests at least against other advanced tools), as this will be the main use for the software in practice.

Another conclusion from the analysis is that, despite the fact that SAFIR offers the use of solid 3D FE for thermal and structural analysis, these have been scarcely subject to validation by users. This can be both a consequence of the fact that these elements have been included only recently in the software, but may also indicate that these still represent big computational efforts that most users do not want to cope with considering that, even at room temperature, building structures are typically modelled with oriented elements such as trusses, beams and shells.

The qualitative analysis of the results yields a clear visualization of the level of accuracy of the software, by an easily interpreted graph that sums up the results of the comparisons made by the users. The review of the comments made by the users allow to clearly identify the types of analyses for which the program returns accurate results and what are the main constraints when using the software.

5 CONCLUSIONS

The analyses presented in the paper allow drawing the following main conclusions:

- Benchmarking examples should include sensitivity analyses. Indeed, the results of a code should be proven not to be disproportionately sensitive to input parameters such as the size of the elements or the time step. Also, if any software would require extremely small elements and/or extremely short time steps to achieve satisfactory results, this should be put to the attention of the users.
- The results given for the DIN for some of the examples are determined by “approved software”. Some of the reference values are not matched by other software which, on the other hand, yield similar results between them. The assumptions made in calculating the reference solutions

should be mentioned to allow determining the reasons of eventual deviations between the tests and the simulations.

- The benchmarking examples currently available for structural fire analysis codes do not cover sufficiently the range of applications commonly found in the literature. It is notably urgent to add new benchmarking examples with steel and concrete shell finite elements and with timber structures, preferably at an international level.
- Failure criteria should be clearly mentioned when a mechanical calculation must be compared with the results of an experimental test of other software, if the ultimate resistance or fire resistance are being considered.
- Meta-analyses of comparisons of results with real-world structures offer a great way to provide additional validation to a software, by delivering insight about the quality of the results obtained and the typology of the comparisons made.

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