NAFEMS World Congress 2025 – Certification by Analysis: A Selection of Case Studies

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Abstract

Ensuring the compliance to regulatory requirements is a mandatory for many products to be allowed on the market. The assessment of product performance is largely based on physical testing of a few samples and, possibly, monitoring of the production process. In order to reduce cost and time-to-market associated to the certification process, manufacturing companies have increased their efforts to establish numerical simulations as a legitimate alternative to physical testing, thus introducing the notion of "Certification by Analysis" (CbA). In some sectors, certification bodies responded to the industrial drive towards virtual testing by developing guidelines and standardised reporting documents to streamline the credibility assessment of the results of numerical simulations without compromising the safety of the certification decision. However, there are still significant differences in the acceptance and maturity of CbA in different industrial sectors. In this contribution, the basic elements of CbA will be reviewed and illustrated through the presentation of two well-established cases and a novel one whose feasibility is still under investigation. The role of standards in the specification of product requirements and assessment methods (for physical as well as virtual testing) will be considered, drawing on the work done in the research project STEERING funded by the Swedish Innovation Agency (VINNOVA). The review will focus on the identification of similarities and differences in requirements, methodologies, and challenges faced by manufacturers and certification bodies. The analysis of established cases provides the starting point to investigate the role of CbA in novel or existing applications where product certification relies exclusively on physical testing.

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1. Introduction

The International Organization for Standardization (ISO) formulated a general definition of certification that applies to virtually any type of material or immaterial product: "*The provision by an independent body of written assurance (a certificate) that the product, service or system in question meets specific requirements*" [1][2].

Several types of certification schemes can be developed consistently with the above definition. Figure 1 shows a generic model of certification processes based on the ISO definition, illustrating the main activities performed by different stakeholders. Every certification scheme is developed within a regulatory framework that stipulates the legally binding requirements at the highest level, not necessarily in quantitative terms (e.g., "the airplane shall be safe to fly during its design service life"). These high-level requirements might be formulated by regulatory bodies governing specific sectors, such as national or international authorities for safety of roads, food, construction sites, etc., or by law-making, political institutions such as parliaments.

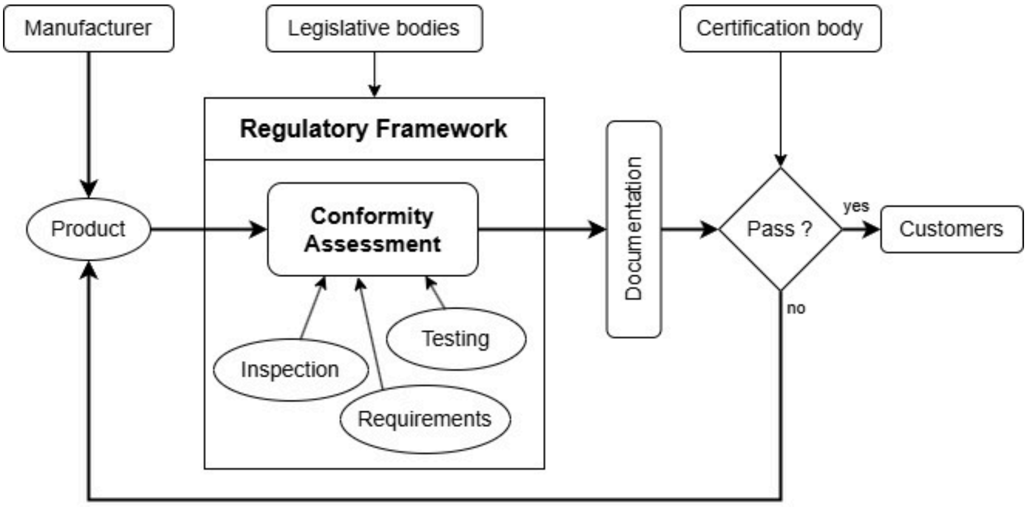

Figure 1: A general process model for product certification schemes, highlighting the main activities and stakeholders.

Regulatory requirements are translated into technical requirements that the product must be proven to fulfil to be approved for the market. The specification of technical requirements might be already part of the regulatory framework, for example by reference to existing technical standards, or it might be stated by certification organizations that are responsible for issuing certificates in a sector.

The "conformity assessment" box in Figure 1 includes all the activities carried out to verify the compliance of products to regulatory requirements, such as testing in controlled environment, inspection of production plants, design review, etc. Depending on the product and the certification scheme, the responsibility to conduct conformity assessment activities might be attributed partly to the manufacturers and partly to certification bodies, or they might even require the involvement of independent, third-party organizations. The documents describing the procedures for conformity assessment might be public (e.g., typical in construction industry) or confidential (e.g., typical in aviation industry), and they might be developed in cooperation with external parties such as universities and independent research institutes.

Documentation of the results of conformity assessment activities plays a crucial role in the certification decision, since the direct participation of certification bodies to these activities (through, for example, attendance to physical tests or sharing of computational models) is often quite limited. Therefore, documentation of tests, inspections, and analyses must typically comply to specific requirements regarding the content and its level of detail.

In order to reduce the considerable costs entailed by certification procedures, numerical simulations have attracted a growing interest in recent years as alternative means to demonstrate product compliance to regulatory requirements, leading to the concept of Certification by Analysis (CbA) [3-5]. There are two main scenarios where numerical simulations enter certification:

1) Manufacturers use numerical models to predict the behaviour of the product under test conditions, possibly optimizing its performance with respect to it, thus minimizing the risk for failing the certification test. However, only the results of physical tests are admitted as evidence to support the certification decision.
2) Numerical simulations are accepted as a means to verify the compliance of products to the requirements stipulated in the certification scheme.

In both scenarios, numerical simulations provide a valid alternative to physical testing only if their predictions are sufficiently accurate for all the test cases required by the certification scheme. Scenario 1) can be considered as a natural extension of the application of Computer Aided Engineering beyond product design and development, where numerical simulations are well established as analysis tool since decades. While in Scenario 1) the definition of criteria and processes to assess the credibility of simulated test results is addressed exclusively by the manufacturer, in Scenario 2) even the certification bodies must establish them.

The basic elements to consider in the assessment of the credibility of numerical simulations are briefly reviewed in Section 2. The challenges posed by CbA to Certification Bodies are illustrated in Section 3. Sections 4-6 report brief accounts of certification cases where numerical simulations play (or they might play) a central role, even though the concept of CbA is not formally acknowledged. Finally, some conclusions and suggestions for future work are reported in Section 7.

2. Credibility Assessment of numerical simulations

Several frameworks for credibility assessment of numerical simulations have been proposed in the literature, such as the PCMM [6][7], the NASA 7009 Standard for Modelling & Simulation (M&S) [8], and others [9 – 16]. Most of these methodologies share a common conceptual basis (e.g., the definition of "model verification" as clearly distinct from "model validation") and the high-level structure of the assessment procedure, which can be schematized as in Figure 2. Differences among the various procedures are found in the scope, attributes to evaluate, suggested practices, and level of standardization. For some examples of application in the context of Quality Assurance of numerical simulation, we refer to [17].

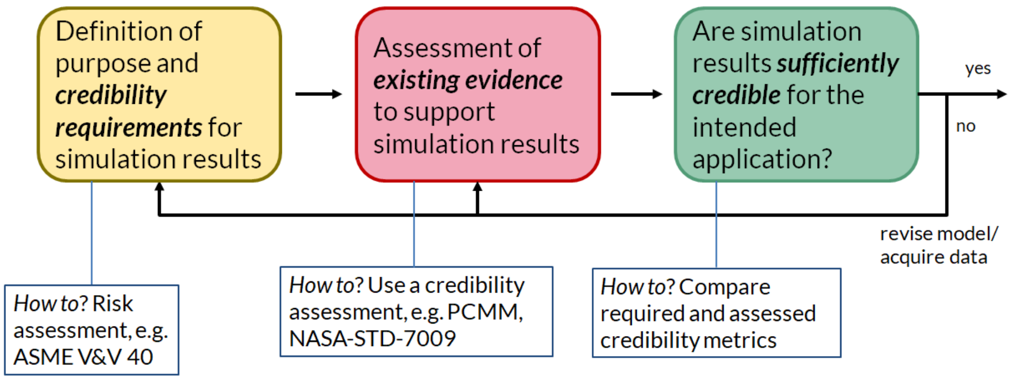

Figure 2: Conceptual model of credibility assessment process for numerical simulations

According to the general model shown in Figure 2, the formulation of credibility requirements is the first step of the assessment process. The trustworthiness of simulation results is often measured in terms of bounds on the largest acceptable deviation between model output and corresponding experimental data. This approach reduces the somewhat vague notion of "trustworthiness" to quantitative measures of specific variables which are relevant for the problem that motivates the creation of the model.

The intended use of the model plays a key role in determining the credibility requirements, that is how much deviation from reality is tolerable for the model. The consequences of making decisions based on erroneous predictions from numerical simulations should be carefully considered and balanced with the cost of generating validation data for the model. Several authors suggested that a risk-informed perspective facilitate the systematic formulation of credibility requirements for numerical simulations [18 – 21].

The central step in the process sketched in Figure 2 is the assessment of the available evidence to support the trustworthiness of simulation results. The choices made to build every part of the model, including any simplifying assumption, should be critically reviewed. The accuracy of the data provided to validate the model against reality should be assessed, together with the design of validation experiments. Some attention should be also devoted to the management of simulation data and models, that is the processes established by the model developers to ensure traceability and reproducibility of the results, documentation, archival, and qualification of involved staff.

All these aspects are often encoded into a list of relatively few attributes that are rated on a numerical or qualitative scale, for example from 0 (“poor”) to 4 (“excellent”). In the latest issue of the NASA 7009 Standard, the assessment process considers two separate sets of factors, one related to the development of models and simulations and another concerning their use, denoted as “M&S Capability” and “M&S Results” assessment, respectively (see Appendix E in []). The considered attributes in the two assessment processes are summarized in Table 1. Target values are defined for each factor using a 5-levels rating system (0 – 4) to reflect credibility requirements, and each factor is assigned a score according to the same system (detailed definition for each level are provided in the standard).

Credibility Assessment of Modelling&Simulations (M&S)		
Development Phase	**Use Phase**	**Comment**
-	Use Assessment	*To what extent is it similar to past applications?*
Data Pedigree	Input Data Pedigree	*Are the data used to set up and tun the model adequate?*
Verification	-	*Are the M&S checked for numerical or implementation errors?*
Validation	-	*How well do the simulation results compare with reference data?*
-	Uncertainty Characterization	*Is the uncertainty in the inputs quantified and propagated through the model?*
-	Results Robustness	*How much is known on the sensitivity of model output to the variability of inputs?*
Tech Review	Tech Review	*Has any independent review been conducted? How and by whom?*
Process/Product Management	Process/Product Management	*How the models and related data managed?*

Table 1: Elements considered in the credibility assessment process for computational models and simulations defined in the NASA 7009 Standard [8].

Mapping out the characteristics of models and simulations to an intuitive qualitative scale greatly simplify the last step of the process sketched in Figure 2, that is the verification of the fulfillment of credibility requirements. That is often illustrated graphically using, for example, spider plots like the one shown in Figure 3 (taken from the case study on system simulation developed in the STEERING project), which facilitates the communication of the outcomes of the assessment process to other stakeholders and it gives a clear indication of which areas should be prioritized for improvement. The list of attributes shown in Figure 3 differs from that given in Table 1 as it referred to the version of the NASA 7009 Standard that preceded the current one issued in March 2024.

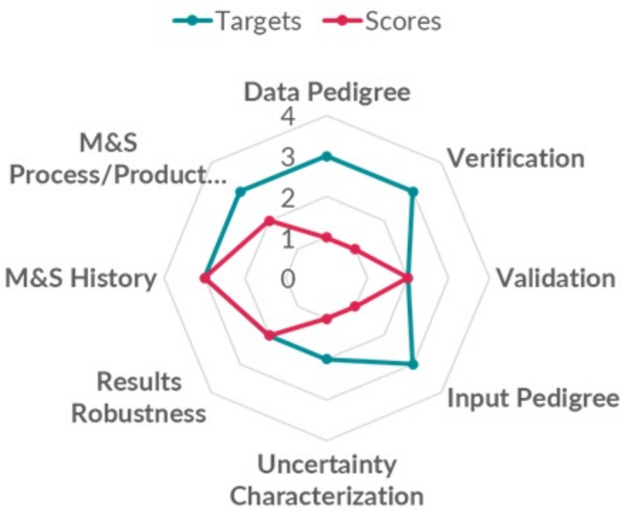

Figure 3: Example of spider plot to visualize the fulfillment of credibility requirements according to the NASA 7009 Standard (version 2016/A, preceding the current one), extracted from a case study developed in the project STEERING [17].

3. The regulatory perspective

The overall interest towards Certification by Analysis was driven from the beginning by industrial stakeholders searching for viable strategies to reduce the costs entailed by the certification process. While several cases are found described in the literature from the industry perspective, the position of Certification Bodies on the subject is comparatively much more rarely exposed. One of the most lucid illustrations can be found in the contribution of H Ross presented at the NAFEMS seminar "Simulation supporting certification", held in 2021 [22].

Some of the challenges posed by CbA discussed in that contribution are summarized below:

- Certification Bodies have access only to limited information about numerical simulations, which typically does not include the models used to generate the results. The data required for certification purposes are normally delivered through written reports, but the type of information and its level of detail may vary significantly among different manufacturers if they do not have to follow standardized forms or guidelines. The computational model is often regarded as a black box by Certification Bodies.

- Building trust in numerical simulations to support certification processes demands to go beyond just the validation of the results. An adequate quality management system should be in place for all the phases of the models' lifecycle, from development to final archival. Certification Bodies should review the procedures set up by product manufacturers to ensure traceability of models and data, verification of software tools, and qualification of personnel.

- There are many types of numerical simulations that address a broad variety of engineering problems and are carried out with many different software tools. It is impossible for Certification Bodies to cover the full range with their own internal resources and expertise. There is always time lag between the *adoption of numerical simulation technologies by manufacturers* and their *acceptance in regulations for the verification of product compliance.* In recent years, there have been cases of Certification Bodies that took initiatives to shorten that time lag, for example the Food & Drugs Administration (FDA) [23] and NASA [24] in the USA, and the European Aviation Safety Agency (EASA) [25].

Certification Bodies are responsible for defining an assessment process that is practically viable in terms of cost and time and uncompromising about any safety concern that might arise from the approval of the product. Minimum requirements for documentation of simulation results are necessary to facilitate mutual understanding between manufacturers and Certification Bodies, and to ensure the efficiency of the review process, although they are generally not sufficient. Valuable insights on how to structure the review process of numerical simulations can be found in the analysis of Kazier [26].

The importance of properly weighing the risk of relying on numerical simulations in product certification can hardly be overstated. There are also risks entailed by using exclusively physical testing, because not all the possible conditions experienced by the product during its service life can be adequately reproduced in laboratory environment. Furthermore, measurements are characterized by uncertainty due to technological limitations, natural variability, and selection of tested specimens. Quality management systems for testing laboratories are established to control the level of uncertainty in measurements and minimize the occurrence of errors, and this is the central part of accreditation requirements as dictated, for example, by the ISO 17025 standard [27]. This general “safety net” has no counterpart in certification processes where numerical simulations are accepted as means to prove compliance. This point was illustrated in the study conducted at RISE on standardized testing of steel beams under fire loads [28].

Two interlaboratory test campaigns were carried out in parallel on the setup described by the standard EN 1363 [29], one based on physical measurements and the other on numerical analysis. The outcomes of the computational study showed a larger spread than their experimental counterpart, giving less-conservative indications on the performance of the test object in about 13% of the cases. Both types of results were derived following all the stipulations in the regulations and relevant technical standards, which made them equally acceptable from the certification standpoint. The primary lesson learned from that study was not to establish physical testing as intrinsically more reliable than virtual testing, but rather to support the inclusion of specific criteria to regulate the use of numerical simulations in product certification.

It is worth noticing, that the lack of requirements on providers of simulation services for certification is not due to the absence of reference documents to define and implement them. The NAFEMS standard for numerical simulations [30] provides comprehensive guidance to define, measure, and improve the fulfilment of requirements that impact on the credibility of numerical simulations for engineering applications. This standard is built upon the interpretation and adaptation of the general ISO 9001 standard to the context of numerical simulations. The adoption of the NAFEMS standard is done on a voluntarily basis, and there are no examples of certification process that mandate it as a prerequisite to admit numerical simulations as a means to prove compliance to regulatory requirements.

4. Case study 1: scaffolding systems

Prefabricated scaffolds are commonly used as temporary structures in construction industry. In order to ensure adequate safety conditions for construction workers, their access to market is rigorously regulated in all European countries. The regulatory framework is formally established at the national level, whereas technical requirements and testing procedures are described in harmonized standards to secure homogeneous safety levels and recommended practices in all countries that participate to the European common market.

The AFS 2013:4 regulations issued by the Swedish Work Environment Authority stipulate the requirements for the safe installation and use of these temporary structures [31]. The key prerequisite for prefabricated scaffolds to be sold on the Swedish market is that they must be awarded a Type Control certificate issued by an accredited certification body within the European Economic Area. AFS 2013:4 refers to the harmonized European standards EN 12810 [32] and EN 12811 [33] for the technical requirements and guidance on how to assess the conformity of products to the requirements.

As accredited certification body and test laboratory, RISE has the technical capacity to provide services for conformity assessment as well as the legal authorization to issue the certificates. To maintain its status of accredited laboratory, RISE must pass yearly inspections by the Swedish Board for Accreditation and Conformity (SWEDAC).

According to the EN 12810 and EN 12811 standards, the structural performance of scaffolding systems is categorized in four possible Load Classes which characterize the conditions under which the systems can be used safely. The Load Class is the main information reported on the Type Certificate. The procedure to determine the Load Class followed at RISE has been developed and applied at the institute for more than two decades, relying on a combination of physical testing and nonlinear Finite Element Analysis performed in the software package ABAQUS. The method is summarized graphically in Figure 4, whereas full documentation is available in internal reports [34][35] as well as in several publications [36][37].

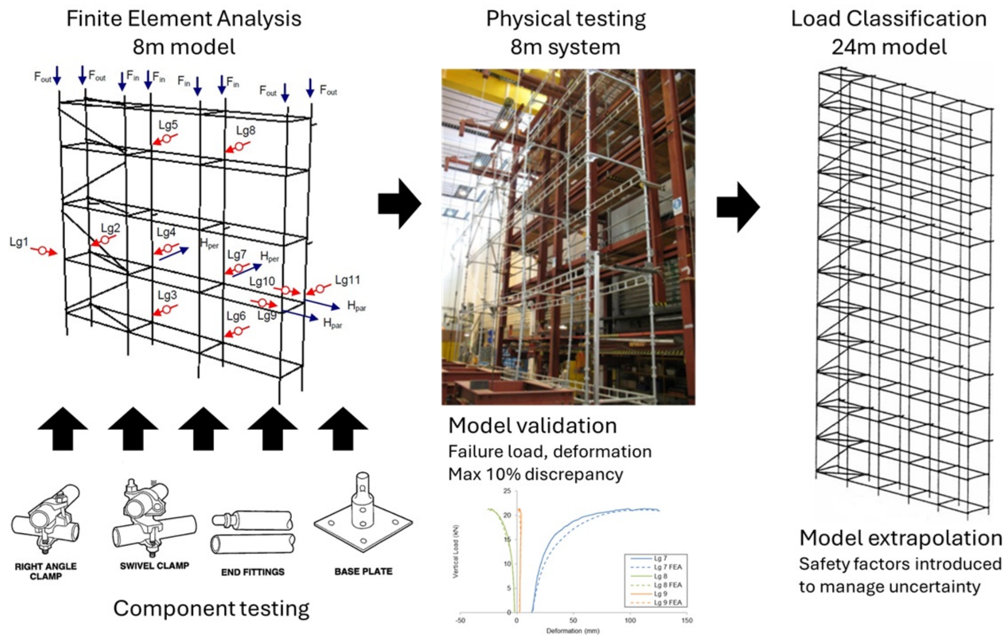

Figure 4: Schematic representation of the process developed at RISE to determine the Load Class of scaffolding systems.

A numerical model of the scaffolding system is first created in the ABAQUS preprocessor module with the geometry shown in the leftmost part of Figure 4: 8m-height and 9m-width, divided in 3 bays, which matches the dimensions of the setup available at RISE laboratory for physical testing. Component tests are carried out to determine model parameters for the properties of the connections between structural elements of the scaffolding system, particularly the gap, stiffness, and strength. Material model parameters are obtained from standardized tests on specimens extracted from actual components.

An 8m-high section of the scaffolding system is mounted in the testing facility and loaded vertically until failure occurs, typically by buckling or exceedance of component strength. The applied load is monitored and displacement measured at several locations (see Figure 4). A nonlinear stress analysis is conducted in ABAQUS on the scaffolding system model using the Finite Element Method and taking into account the nonlinear effects arising by large deformations and plasticity. The model includes also imperfections measured in the test system, e.g. the inclination of some elements. The vertically applied load is increased until buckling or material failure occurs in some component.

The results from the test and its numerical simulation are compared to validate the model. A relative discrepancy of up to 10% between the measured and simulated failure loads and deformations is considered acceptable to qualify the 8m-model as validated.

The validated model is then expanded to a 24m-high, 15m-wide section of the scaffolding system. Material properties and loads are updated to the nominal values prescribed the standard. The maximum load that the system can sustain in each case required by the classification procedure is computed using the same nonlinear Finite Element Analysis used for the 8m model.

Several observations can be made on the certification process for scaffolding systems that stimulate the reflection on general aspects of CbA:

- A central role is attributed to numerical analysis in the governing technical standards. However, no specific quality requirements are stipulated for the computational models. An investigation of PCMM as quality assurance method for the scaffolding system models was conducted in project STEERING, which highlighted particularly the difficulty to formulate adequate credibility requirements without support from the regulatory framework [17]. Regarding possible requirements for the management system of the models, the following considerations were given in [38]: "*Much of the quality assurance of internal processes, methods and work procedures instead hinges on our compliance with the more general requirements of the ISO 17025 for accredited labs, which is regularly reviewed in external audits. These requirements concern not only the experimental part of accredited methods, but also all related numerical activities, such as post-processing scripts and simulations. By fulfilling requirements of ISO 17025, one more or less automatically complies also with ISO 17025 and much of the NAFEMS QSS*[2]*, as for example allocation of personnel with documented competence and training, change control of scripts and documents, internal reviews, etc.*" On the basis of these considerations, the external audits are expected to be conducted by personnel with adequate qualifications in experimental as well as computational methods.
- The uncertainty in experimental data used for model calibration and validation is evaluated to comply with accreditation requirements set by the ISO 17025 standard. The uncertainty in the load classification outcome is handled by introducing safety factors in the design values of loads and resistances used in the computational models, according to the general principles of Eurocode [39]. Although this is a pragmatic and widely accepted approach to manage uncertainty, the degree of conservativeness of the design is hard to determine (which might lead to unnecessary and costly overdesign), as well as the identification of the design variables and parameters that have the largest contribution on the uncertainty of model output. The explicit

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[2] That is, the previous name of the current NAMES EQMS.

consideration of uncertainty in the 24m model appears to be particularly important in this case, as the model differs from the one that is validated experimentally, not only because of the larger size, but also for the evaluation of material properties (nominal values are used instead of characteristic values derived from component tests). A first step towards a full quantification of model uncertainty was the screening analysis on 38 input parameters reported in [38], which was conducted using a Plackett-Burman Design of Experiments with plausible intervals of variation. The most influential parameters were found to be the design moment in the connection between vertical elements and the gap in the connection between vertical and horizontal elements.

- There are no requirements on model verification (e.g., stability of the numerical solution with varying levels of geometry discretization) in the current regulatory framework and conformity assessment process.
- The validation criterion for the 8m model does not take into account the uncertainty in experimental and numerical data.

5. Case study 2: vehicle restraint systems

Vehicle restraint systems are elements of road infrastructure designed to resist the impact of colliding vehicles and deflect them back to a safe trajectory. They exist in many types, adapted for delivering their containment function in different parts of the road infrastructure: safety barriers, wire rope systems, vehicle parapets, terminals (i.e., end sections of safety barriers), transitions, crash cushions, etc.

Vehicle restraint systems are construction products subjected to the rule of the Construction Product Regulation (CPR) of the European Union [40]. As a prerequisite for being allowed on the European common market, vehicle restraint systems must be marked with the CE symbol and accompanied by a Declaration of Performance that specifies the key characteristics of their expected performance (e.g., limited deformation after vehicle collision). The manufacturers are responsible for the veracity of the information reported on the Declaration of Performance. Since a common technical standard for vehicle restraint systems has been developed, that is the EN 1317 [41], the CE-marking process stipulates that the properties declared for these construction products must be certified by one organization with the status of Notified Body accredited to provide testing, inspection, and analysis services to verify the conformity to that standard [41]. The overall workflow of the conformity assessment process for vehicle restraint systems is sketched in Figure 5.

The conformity of new vehicle restraint systems to the requirements of EN 1317 must be verified by physical testing, i.e., the so-called Initial Type Tests (e.g., TB11 test is impact of passenger cars). Modified versions of the same system are commonly designed by manufacturers, for example by adding poles or noise barriers. For the modified systems to be admitted on the European common market, the initial certificate must be updated with each variant.

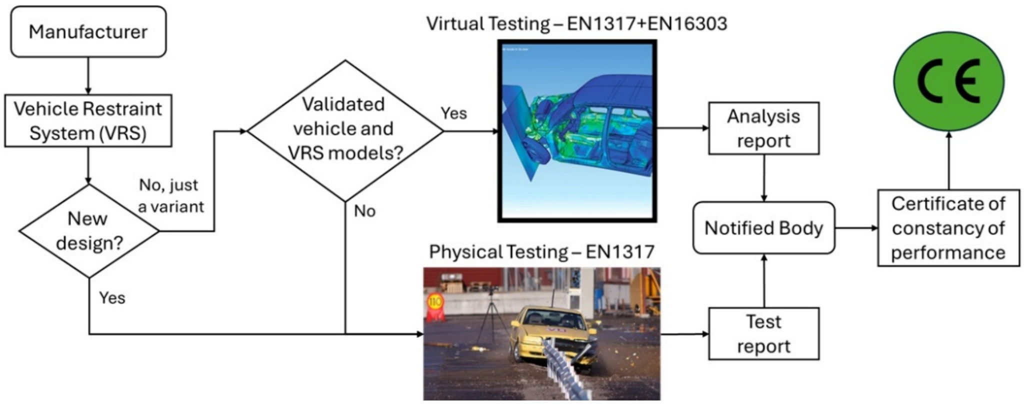

Figure 5: Illustration of the process of acceptance of numerical simulations as alternative to physical testing in the certification of vehicle restraint systems. The certificate issued by the Notified Body is part of the mandatory documentation required to manufacturers of vehicle restraint systems to CE-mark their products.

Conformity assessment of modified systems may be done solely by numerical simulations (i.e., *virtual testing*), provided that the changes do not significantly affect the properties that mostly determine the response of the barrier to impact loads, such as stiffness and Acceleration Severity Index (see Section A.6 in Part 5 of [41]). The decision on the suitability of just numerical simulations to assess the conformity of the altered design is left to the judgement of the assessors from the Notified Body. Requirements on permitted deformation levels depend on where the barrier is installed and the potential consequences of a crash event. For example, bridge parapets must fulfil more stringent requirements than barriers mounted along secondary roads.

Virtual testing has been established in the certification of vehicle restraint systems since several years and the maturity of quality assurance procedures for numerical simulations in this area is corroborated by the existence of dedicated guidelines for model verification and validation, i.e. EN 16303 [42]. The outcomes of virtual tests have the same acceptance criteria as those of physical tests. In addition to that, the EN 16303 guidelines establish the credibility criteria for the computational models of the vehicles and of the restraint systems used to simulate the crash test, most of which are listed in Table 2 (for the definitions of the performance indicators, we refer to the standard [41]).

Both types of criteria are assessed during the review process by the Notified Body, which typically can access only the documentation of the simulation results, but not the models themselves as they contain confidential information about the product that cannot be disclosed outside the manufacturer's organization. Preventing the Notified Bodies to inspect the computational models poses the problem of the integrity of the results presented in the analysis report submitted by the manufacturers. How to ensure that they were derived with the same models described in the report and not just being manipulated to show compliance? This problem was discussed in a recent work, where a possible solution via a dedicated software management system was also described [43].

As a Notified Body with accreditation for the EN 1317 standard and many years of experience on the CE-marking of vehicle restraint systems, RISE developed internal procedures to ensure a thorough and transparent review of the results of simulations presented by manufacturers, minimizing the risk of excessive impact of the subjective judgment of individual reviewers. A few elements are added to those listed in Table 1 in the review process:

1) Risk assessment: what are the consequences of certifying the performance of the product with misleading or nonconservative simulations? Could that lead to considerable damage to individuals, society, economy, or the environment? The higher the risk, the smaller the discrepancy from reality that is admittable for the simulations.
2) Assessment of the level of solution verification, for example via mesh convergence studies or comparison with analytical solutions.
3) Detailed review of modelling choices, e.g., element types, definition of material models, boundary conditions, applied loads, mesh quality, geometry simplifications with respect to drawings, etc.

It is worth noting that all the quantitative validation criteria reported in Table 2 (expressed in terms of some performance indicator X) are all in deterministic form, that is $|X_{exp} - X_{sim}| <$ "max allowed deviation", without consideration for the uncertainty that affects the experimental as well as the computational data. This type of validation metrics might be misleading, as discussed in the literature. Furthermore, Section 8.4 of [42] recommends to document and justify "important model parameters" without specifying how the importance should be characterized. Global sensitivity analysis might help to systematically check the robustness of model output with respect to input variations. Both these points would require considering explicitly the uncertainty in model inputs, and structure, which would entail more additional work with respect to the current accepted practice.

Asking for more checks than those strictly required by the EN 16303 guidelines is likely to meet some resistance from the manufacturers. An open attitude to dialogue and clear communication should be pursued by all the parties involved, in order to avoid misunderstandings and unnecessary delays in the certification process.

Anyway, the current certification process is ultimately relying quite heavily on the judgment of the individual reviewer. Novel tools such as proposed in [43] or applications of Artificial Intelligence methods (e.g., algorithms trained on open benchmark simulations to detect possible anomalies in the results of black-box models) might provide useful assistance to human reviewers and reduce the margin for errors in the simulation review process.

Prerequisites for acceptance of virtual crash test		
Verified and validated vehicle model	Required	Section A.6 in Part 5 of [41]
Verified and validated model of parent variant of vehicle restraint system	Required	
***Validation* criteria for virtual crash test (qualitative)**		
Containment, rollover, exit box, wheel trajectory, failure of longitudinal elements, failure modes, penetration of test item parts in the vehicle	It shall be the same in physical and virtual tests	Tables 2 – 5 in [42]
Final shapes	The post-crash shapes of the physical and simulated test object shall be reported.	Sec. 8.3.7 in [42]
***Validation* criteria for virtual crash test (quantitative)**		
Dynamic deflection, D	$\lvert D_m - D_{VT}\rvert \leq 0.1 + 0.1D_m$	Table 6 in [42] m = Real Test VT = Virtual Test
Working width, W	$\lvert W_m - W_{VT}\rvert \leq 0.1 + 0.1D_m$	
Vehicle intrusion, VI	$\lvert VI_m - VI_{VT}\rvert \leq 0.3 + 0.1D_m$	
Tolerances for severity indices		
ASI / ASI time	$\pm$ 0.1 / $\pm$ 0.05 s	Table 7 in [42]
THIV / Time of flight	$\pm$ 3 km/h / $\pm$0.05 s	Tables 8 in [42]
Velocity time history	$\pm$ 4% initial vel. / $\pm$ 0.01 s	Sec. 8.3.9 in [42]
Yaw angle time history	$\pm$2.5°/ $\pm$0.01 s	
***Verification* criteria for virtual crash test**		
Total energy variation	< 10% initial value	Table 9 in [42]
Hourglass energy of solution at any time	< 5% initial total energy	
Hourglass energy of solution at the end	< 10% internal energy at the end	
Part with largest hourglass energy	< 5% internal energy at the end	
Total added mass	< 5% total initial mass	
Part with largest added mass	< 0.5 kg + 10% initial mass	
Moving parts added mass	< 5% initial mass of moving parts	

Table 2: Requirements for test results and computational models used in virtual testing for regulatory approval of vehicle restraint systems in Europe.

6. Case study 3: wind turbine blades

The example discussed in this section is not an established example of CbA like the cases presented in Sections 4 and 5, but rather the brief account of ongoing work to build a reliable framework for CbA in an area where current testing methods for certification are subjected to severe limitations.

The COST Action "*Advanced Composites under HIgh STRAin raTEs loading: a route to certification-by-analysis*" (HISTRATE) is a 4-year network initiated in 2022 to boost knowledge sharing and collaboration among academic researchers, industrial stakeholders, and certification bodies to accelerate the development and implementation of composite structures subjected to high strain rate loads such as impact and blast [44].

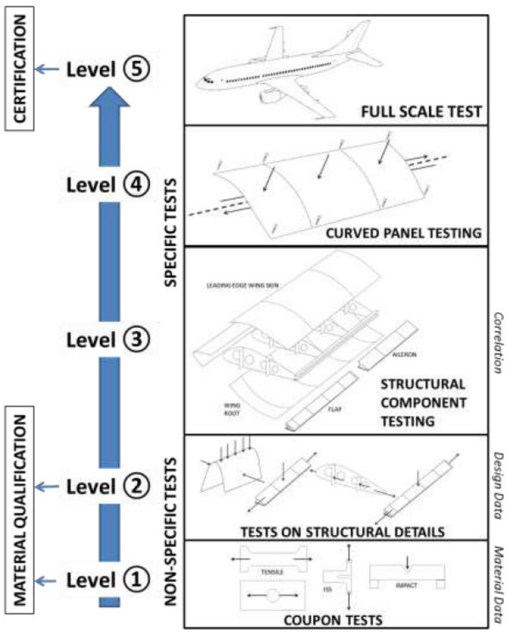

Figure 6: Workflow of the building block approach for testing composite structures.

The performance and strength of composite structures, including safety-critical structures, are currently established incrementally through analysis and experimental tests conducted using specimens of different sizes and complexity. This process utilizes the so-called "building block" or "testing pyramid" approach shown in Figure 6 with tests at different scales: (i) Coupon, (ii) Structural detail, (iii) Component, and (iv-v) Sub-structure or full structure. The "building block" approach is a systematic methodology and constitutes the backbone of certification processes, especially for composite aero, wind and car structures. Most of certification tests are conducted at the coupon level, whereas far fewer certification tests are conducted at the subsequent higher pyramid levels. The complexity, cost and time of each test escalate up through the testing pyramid. The building block approach has been validated and is widely used for certification of primary structures made of metals and composites subject to static and dynamic loading.

In many practical situations, safety-critical structures are subjected to loading at high to very high strain rates. These extreme loading conditions are often the result of undesirable events such as bird strike, blast, impact, crash, lightning strike. Surprisingly, although the material and structural response under extreme loading differs significantly from its response to quasistatic loading, extreme loading is outside the scope of standard design approaches. For most materials, knowledge of the behavior under extreme conditions is still limited and not sufficiently mature to be incorporated into design guidelines.

The network established by HISTRATE includes a broad range of technical expertise that reflect the complexity of the challenges posed by the design and testing of fibre-reinforced composite materials under high-strain rate loads: materials testing, full field and local strain measurements and crack propagation, in-situ and post-impact damage characterization, multiscale analysis for design. Different techniques are going to be integrated in a framework designed to ensure a robust, efficient, and transparent verification of product compliance to requirements, which is essential for certification. Two main challenges were identified since the early stage of HISTRATE: the need for new testing methodologies tailored to determine high-strain rate material properties, and a tighter integration between physical testing and simulations.

Several case studies are under development to fill existing knowledge gaps and to explore different routes for integration of experimental and computational techniques. The list of applications under study include the inclusion of impact load cases (e.g., bird strike, hailstorm) in the certification of wind turbine blades. The characterization of impact damage on wind turbines and resulting costs and loss of performance were reviewed [45].

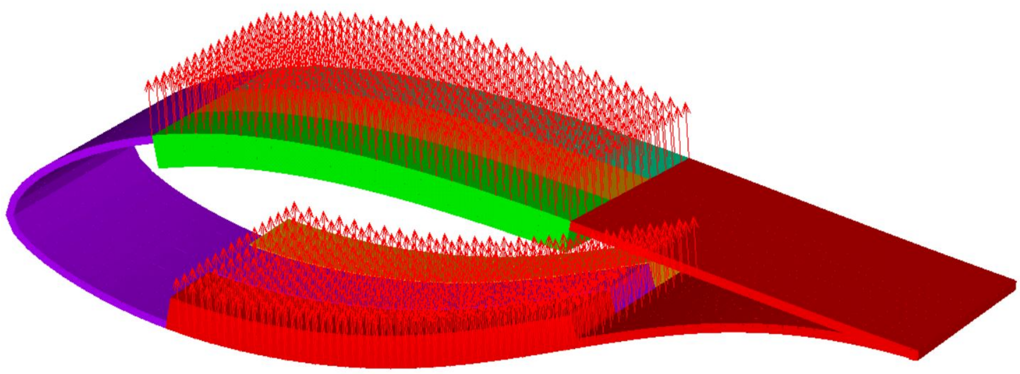

Figure 7: Geometry of the model proposed to analyze impact loads on wind turbine blades produced with the one-shot technology at Cartflow.

The current certification procedures for wind turbine blades are regulated by the document OD-501 issued by the International Electrotechnical Commission (IEC) [46] and the DNV-DS-J102 standard issued by DNV [47]. The mandatory testing procedures are designed to determine the strength of the blades under quasi-static and cyclic loading conditions, whereas impact and shock are not covered.

The questions that are going to be investigated in the study are both methodological and practical, some examples are given in the list below:

1) One or several quantitative damage indicators should be introduced to provide a concise description of the state of the blade after the impact.
2) The damage indicator(s) could be evaluated by several methods (experimental, computational, or combinations thereof). What requirements should be stipulated for the conformity assessment procedures to ensure a comparable margin of uncertainty for all the methods?

In order to address the questions in the above list (and others from all the case studies developed within HISTRATE), a valuable reference has been identified in the outcomes of the project PLASA2, which demonstrated a feasible approach to introduce virtual testing in existing certification processes in the railway industry [48][49]. Several lessons learned from that project could be translated into the scope of HISTRATE, for example the key role that early engagement of certification bodies and standardization groups can play to benchmark the results of advanced engineering projects and facilitate their acceptance in industrial practice.

7. Conclusions and outlook

The problem of defining a transparent and practical process to assess the predictive capability of numerical models is getting more relevant as product development relies more and more on virtual testing.

The regulatory framework should clarify to what extent numerical simulations might be admitted in the certification process and provide guidance to set adequate credibility requirements (e.g., setting prescriptive limits to model characteristics).

Certification Bodies need support to define rigorous yet practical procedures to build an acceptable level of trust in the results of numerical simulations. A stronger emphasis should be given to the explicit quantification of uncertainty in computational models, in parallel to what is already established for physical measurements. Probabilistic methods offer a rigorous framework to characterize model robustness in a way that could be mutually understandable for both product manufacturers and certification bodies. The impact of simplifying assumptions and calibration procedures on the spread of model output should be routinely requested as part of the mandatory documentation.

Earlier projects that led to concrete implementation of CbA schemes should be used as reference cases, and lessons learned there should be disseminated and adapted in novel applications.

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