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Quality processes for bridge analysis models

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Abstract. The design of bridges often involves the use of structural analysis models of varying degrees of complexity. Superstructure design models vary from approximate one-dimensional line girder analysis models to complex two- and three-dimensional finite element analysis models. Substructure and foundation models often consider soil-structure interaction, second-order effects, dynamic response for seismic analysis, and interaction with the superstructure. A variety of analysis methods and associated software are used to create and analyze these models and obtain the analysis output. This process can be quite complex with a large number of input parameters and significant amounts of output data. A study was recently conducted in the United States to identify and document state departments of transportation (DOT) practices related to the quality processes for bridge structural analysis models. The study documents the written and informal processes for identifying appropriately qualified staff including in-house personnel and consultants; choosing an appropriate analysis method and software; validating the analysis software; modeling a bridge structure with proper approaches and assumptions; verifying the analysis results; and reconciling discrepancies between independent models. Information was gathered through a literature review, a survey of all DOTs, and follow-up interviews with five selected agencies as case examples. The survey was completed by 51 DOTs, including 50 states and the District of Columbia, yielding an overall response rate of 100%. This paper aims to summarize the main findings and refer readers to the relevant references. In addition, commonly misunderstood concepts and processes, such as verification, validation, uncertainty, error, and calibration, are clarified.

Keywords: Bridge analysis; Consultant projects; In-house projects; Quality assurance; Quality control.

1. Introduction

The design of bridges often involves the use of structural analysis models of varying degrees of complexity. Superstructure design models vary from approximate one-dimensional line girder analysis models to sophisticated two- and three-dimensional finite element analysis models. Substructure and foundation models often consider soil-structure interaction, second-order effects, dynamic response for seismic analysis, and interaction with the superstructure. A variety of analysis methods and software can be used to create and analyze these models. This process can be quite complex with a large number of input parameters and significant amounts of output data.

The engineer must understand the limitations of the analysis method and software, possess experience in developing analysis models with proper approaches and assumptions, and correctly interpret the results. An appropriate understanding of the expected behavior of the structure is also required to assess if the predicted behavior represents the actual performance of the structure. A simple check of the program input values is not an adequate way of ensuring the accuracy and validity of these models. Quality assurance (QA) and quality control (QC) are two essential processes for the quality management of analysis models. Verification and validation (V&V) play a critical role in the QA/QC process.

A study was recently conducted in the United States to identify and document state Departments of Transportation (DOT) practices related to the quality processes for bridge structural analysis models. The study documents the written and informal processes for identifying appropriately qualified staff, including in-house personnel and consultants; choosing an appropriate analysis method and software; validating the analysis software; modeling a bridge structure with proper approaches and assumptions; verifying the analysis results; and reconciling discrepancies between independent models. In addition, the study identified gaps that could be addressed to enable state DOTs to benefit more effectively from the quality processes for bridge analysis models.

This paper aims to summarize the main findings and refer readers to the relevant references for the complete study details. In addition, commonly misunderstood concepts and processes are clarified.

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2. Commonly misunderstood concepts and processes

Quality assurance and quality control are two essential aspects of quality management. While some quality assurance and quality control activities are interrelated, they are defined differently. QA activities and responsibilities cover virtually all of the quality system in one fashion or another, while QC is a subset of the QA activities (American Society for Quality, 2023) (Fig. 1). Elements in the quality system might not be specifically covered by QA/QC activities and responsibilities but may involve QA and QC (Technical Committee ISO/TC 176, 2015).

Verification and validation (V&V) are indispensable components of QA/QC processes in computational modeling of bridge structures. V&V are the processes by which evidence is gathered to determine the accuracy of the computer model for specified conditions. These accuracy results, along with uncertainty quantification, contribute to the determination of the credibility of the model for the conditions of its intended use (ASME V&V 10-2019, 2020).

While the terms verification and validation are often used interchangeably in casual conversations in bridge engineering practice, they have, in fact, quite different meanings. Stated succinctly, verification deals with 'mathematics' while validation deals with 'physics' (Patrick J. Roache, 1998). Verification assesses the numerical accuracy of a computational model regardless of the physics being modeled, while validation assesses the degree to which the computational model is an accurate representation of the physics being modeled (ASME V&V 10-2019, 2020). Verification uses comparison of computational solutions with highly accurate (analytical or numerical) benchmark solutions whereas validation compares the numerical solution with the experimental results. In verification, the relationship of the simulation to the real world is *not* an issue. In validation, the relationship between computation and the real world *is* the issue (Oberkampf, Hirsch, & Trucano, 2003). The relationships between V&V activities involved are schematically presented in Fig. 2 (Kwaśniewski, 2009).

Verification is defined as 'the process of determining that a computational model accurately represents the underlying mathematical model and its solution' (ASME V&V 10-2019, 2020). Verification has also been described as *'solving the equations right'* (Van Hees, 2013). The fundamental strategy of verification is to identify, quantify, and reduce errors in the computational model and its numerical solution (Oberkampf et al., 2003).

Validation is defined as 'the process of determining the degree to which the model is an accurate representation of corresponding physical experiments from the perspective of the intended uses of the model' (ASME V&V 10-2019, 2020). Validation has also been described as *'solving the right equations'* (Van Hees, 2013). The fundamental strategy of validation involves identifying and quantifying errors and uncertainty through comparison of simulation results with experimental data.

At this point, it is useful to define uncertainty and error. *Uncertainty* is a potential deficiency in any phase or activity of the modeling process that is due to the lack of knowledge, while *error* is a recognizable deficiency in any phase or activity of modeling and simulation that is not due to lack of knowledge (AIAAG-077-1998, 2002). The key phrase differentiating the definitions of uncertainty and error is 'lack of knowledge.' The key word in the definition of uncertainty is 'potential,' which indicates that deficiencies may or may not exist. The definition of error implies that the deficiency is identifiable upon examination (Van Hees, 2013).

One approach for determining the level of uncertainty and its effect on an analysis is to perform a sensitivity analysis (AIAAG-077-1998, 2002). *Sensitivity analysis* is the general process of discovering the effects of model input parameters on the response quantities of interest using techniques such as analysis of variance (Mason, Gunst, & Hess, 2003). When performed after the computational model is verified but before it is validated, a sensitivity analysis can provide important insight into the characteristics of that computational model (ASME V&V 10-2019, 2020).

It is also important to define calibration and put it in perspective. One simple definition of *calibration* is to employ explicit tuning or updating of model parameters associated with an engineering code to achieve improved agreement with existing validation experiments (Oberkampf, Trucano, & Hirsch, 2004; Trucano, Swiler, Igusa, Oberkampf, & Pilch, 2006). As another definition, calibration is a procedure where, through repeated calculations with modified input parameters, the engineer tries to find an 'optimal' set of input data which can provide the model's response closest to the actual experimental data (Kwasniewski & Bojanowski, 2015). The process allows the most common sources of modeling (and experimental) difficulties to be represented as simple mechanical models and calibrated so that the global response of the computational model agrees with the experimental results (ASME V&V 10-2019, 2020). Calibration of the model should be performed only after both code verification and calculation verification have been performed (ASME V&V 10-2019, 2020).

Parametric model calibration determines only the model's fitting ability, not its predictive capability. A model calibrated to experimental results may not yield accurate predictions over the range of its intended use. It is possible that, due to superimposing of errors, the engineer can get good correlation between the experimental and numerical results for a wrong model, defined by incorrect input parameters. Such a situation is often detected when the model is used for a different case with changed input conditions. Furthermore, a complex model with only some of the input parameters 'correctly' calibrated should give a response different from the experimental data due to the indeterminacy of other parameters. (Oberkampf et al., 2004).

As another important definition, *a benchmark* is a choice of information that is believed to be accurate or true for use in verification, validation, or calibration. The fundamental purpose of benchmarks is to draw specific conclusions from their comparison with calculations. In the case of verification, this purpose is to assess the mathematical accuracy of numerical solutions. For validation, this purpose is to assess the physical fidelity for a stated application of the mathematical equations solved in the code. For calibration, the purpose is to choose parameter values that improve the agreement of the code calculations with the chosen benchmarks, in the belief that such tuned accuracy improvement will increase the believed credibility of the code – a goal commonly consider to be incorrect. The choice of benchmarks must vary depending on the purpose of the comparisons (Trucano et al., 2006).

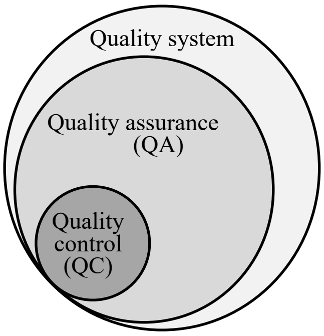

Fig. 1. Relationship between the quality system, quality assurance, and quality control.

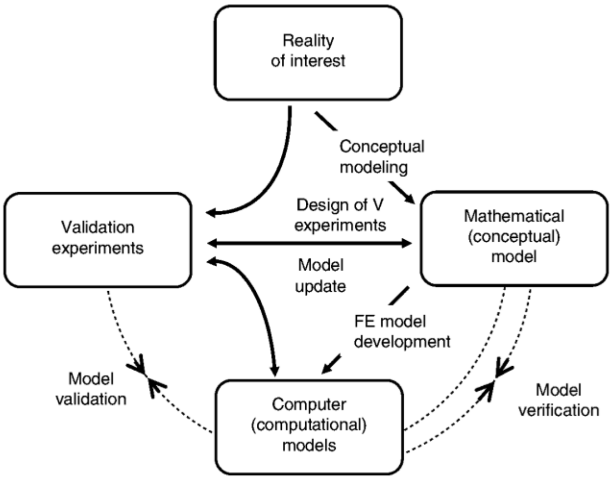

Fig. 2. Relationships between modeling, verification, and validation.

3. State of practice in the United States

To collect the most current information, an online survey was distributed to each DOT's voting member in the AASHTO Committee on Bridges and Structures. The survey included 25 questions grouped in three sections: quantities of the bridge design and evaluation projects undertaken; bridge designs completed by consultants; and bridge designs completed in-house by agencies. The survey was completed by 51 DOTs, including 50 states and the District of Columbia, giving an overall response rate of 100%. In addition, specific information was collected from five selected state DOTs—California, Colorado, Iowa, Louisiana, and New York— as case studies to expand on their quality processes related to bridge structural analysis models. The following section presents a summary of the results obtained from the survey and case studies under four headings.

3.1 Quantity of the Bridge Design and Evaluation Projects Undertaken

The survey asked respondents about the total number of bridge engineers employed by their agencies. As shown in Fig. 3, there is a large variation across the nation. The most represented range is 20 to 40 engineers as selected by 17 DOTs (33%) while the least represented range is less than 10 engineers as selected by 5 DOTs (10%).

Fig. 4 compares the responses from two questions related to the percentage of new bridge design and existing bridge analysis work assigned to consultants. The analysis of responses indicates that the average percentage of new bridge and bridge replacement designs assigned to consultants is 59% while the existing bridge analyses, including load ratings, assigned to consultants is 47%. The complete set of questions and results may be found in Guner (2024).

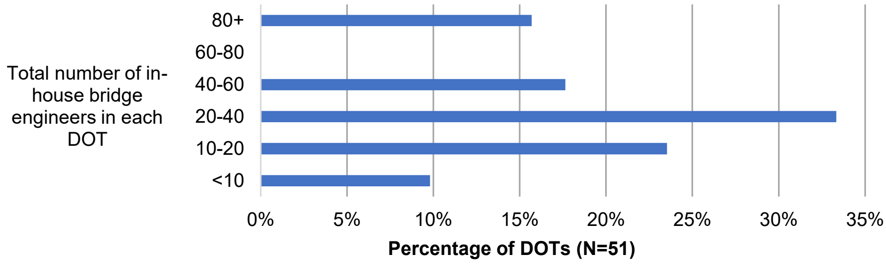

Fig. 3. Number of bridge engineers currently working in each DOT.

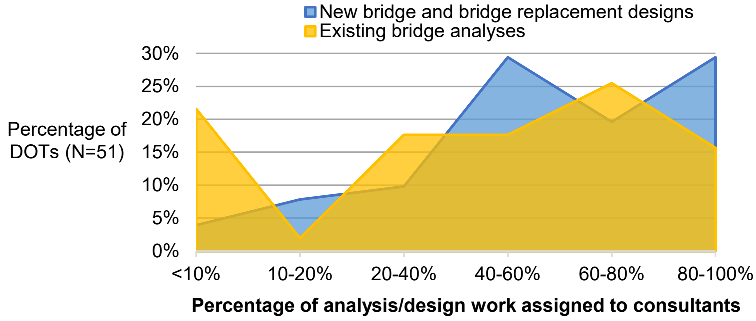

Fig. 4. Comparative DOT responses for new bridge design and existing bridge analysis assigned to consultants.

3.2 Quality processes for the bridge design projects undertaken by consultants

Three questions asked respondents about the presence of processes for certain consultant-related bridge design activities. As shown in Fig. 5, the most common written process, selected by 31 DOTs (61%), is for 'identifying appropriately qualified consultants.' This process also has the least amount of no process responses as only selected by 4 DOTs (8%). The least common written process, selected only by 8 DOTs (16%), is for 'verifying the analysis results obtained from consultants.' 6 DOTs (12%) indicated that this process may be undertaken as defined in the proposal of the consultant.

The respondents were asked how they select appropriately qualified consultants for bridge design projects. They were given three response options. The most common process, as selected by 46 DOTs (90%) is 'proposal evaluation,' while the least common process is 'interview' as selected by 18 DOTs (35%). The geographical distribution of two processes for selecting appropriately qualified consultants is presented in Fig. 6.

The survey asked a follow-up question to 36 respondents whose agencies have pre-qualification requirements, with four response options. As shown in Fig. 7, the most common requirement, selected by 30 DOTs (83%), was "minimum number of similar project experience," while the least common requirement, selected by only five DOTs (14%), was "structural engineer credentials."

The 15 DOTs (29%) which track what methods of analysis are used by their consultants were asked what methods of analysis are used for bridges analyzed by their consultants. As shown in Fig. 8, the most frequently used analysis method is "one-dimensional line girder analysis," while the least frequently used method is "nonlinear finite element method."

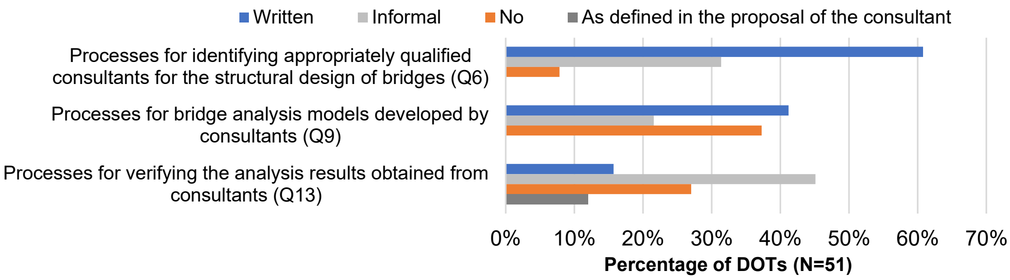

Fig. 5. Comparative DOT responses to three questions on consultant processes.

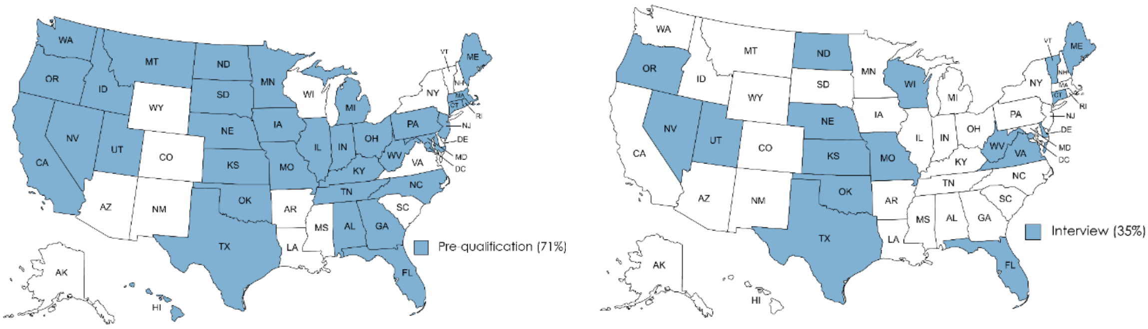

Fig. 6. DOTs with pre-qualification and interview requirements for selecting appropriately qualified consultants.

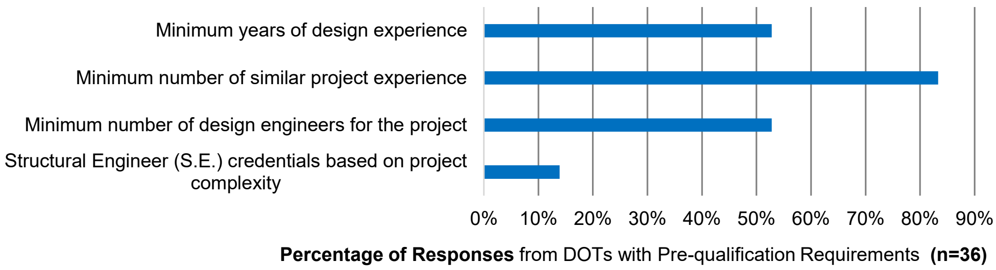

Fig. 7. DOT requirements for the pre-qualification process. Check-all-that-apply type of question.

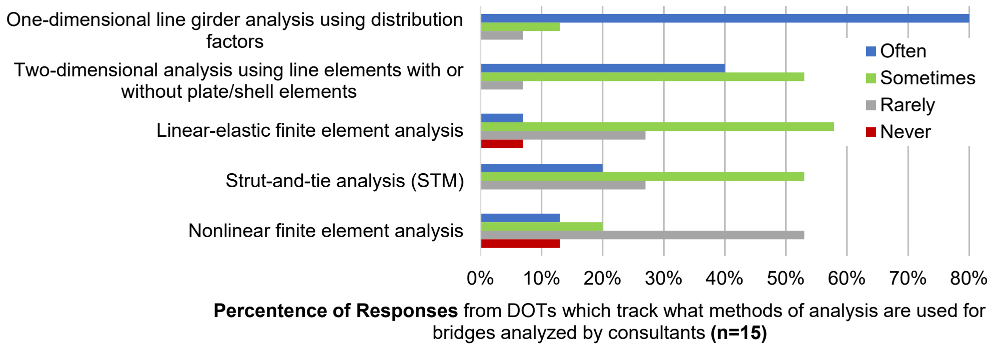

Fig. 8. Methods of analysis used for bridges analyzed by consultants.

3.3 Quantity of the bridge design projects performed in-house by agencies

The respondents were asked six questions on the presence of processes for certain in-house bridge design activities. As shown in Fig. 9, the largest number of DOTs with a written in-house process (for modeling a bridge) is 16 (31%), while the largest number of DOTs with a written consultant process (for identifying appropriately qualified consultants) is 31 (61%).

The respondents were asked what methods of analysis are used for bridges analyzed in-house by their agencies. Fig. 10 compares the percentage of responses from DOTs for the analysis methods used by consultants and DOTs for the "often" frequency. This comparison indicates that consultants use more refined analysis methods.

Fig. 11 shows the responses obtained from 7 DOTs which have written processes for validating the analysis software. The most common response for the "often" frequency, selected by five DOTs (71%), was "analysis engineer decides how to validate." The most common response option for the "sometimes" frequency, selected by four DOTs (57%), was "hiring external consultants."

The respondents were asked whether their agencies have any written or informal processes for verifying in-house analysis results. Fig. 12 shows the responses obtained from 13 DOTs which have written processes for verifying their in-house analysis results. The most common response for the "often" frequency, selected by eight DOTs (62%), was "checking of input variables." "Another team of engineers uses a different method or software" and "analysis engineer decides how to verify" were the other common responses for the "often" frequency.

The respondents were asked whether their agencies have any written or informal processes for reconciling discrepancies between independent models. Fig. 13 shows the responses obtained from eight DOTs that have written processes. The most common response for the "often" frequency was "the same team of engineers works to resolve the discrepancies," selected by five DOTs (63%), followed by "analysis engineers decide how to reconcile," selected by four DOTs (50%). The least common response was "data from field tests and sensor deployment are used," followed by "an external consultant is involved to perform independent checks."

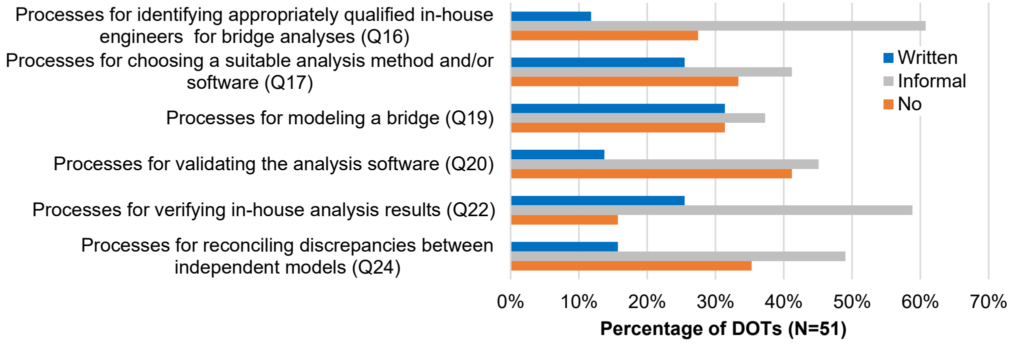

Fig. 9. Comparative DOT responses to six questions on in-house processes.

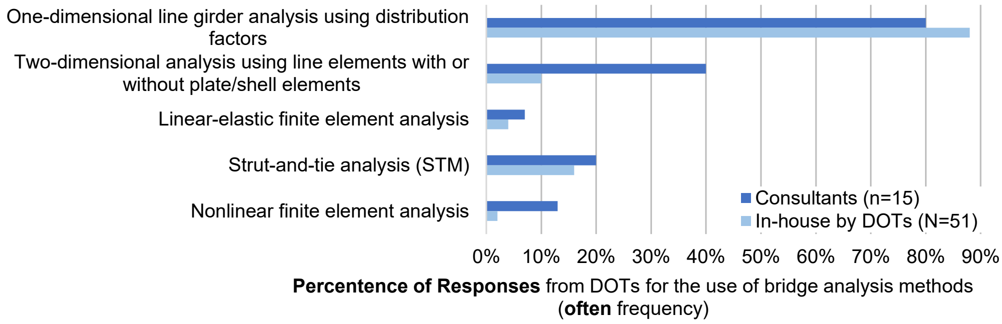

Fig. 10. Comparative DOT responses for methods of analysis used by consultants and DOTs ('often' frequency).

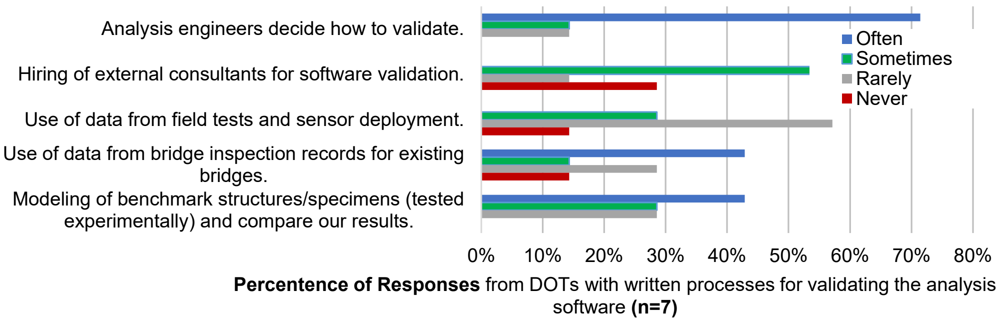

Fig. 11. Methods of validation of analysis software for medium- to high-complexity bridges and substructures that require 2D or 3D analysis models (DOTs with written processes).

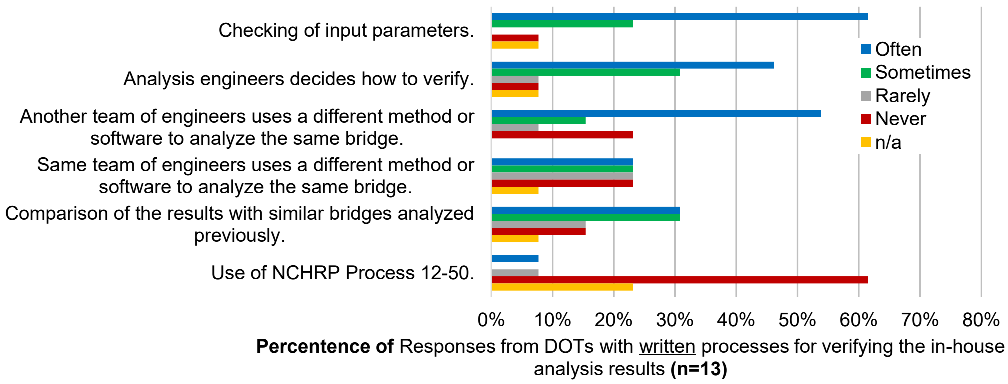

Fig. 12. Methods of verification of in-house analysis results for medium- to high complexity bridges and substructures that require 2D or 3D analysis models (DOTs with written processes).

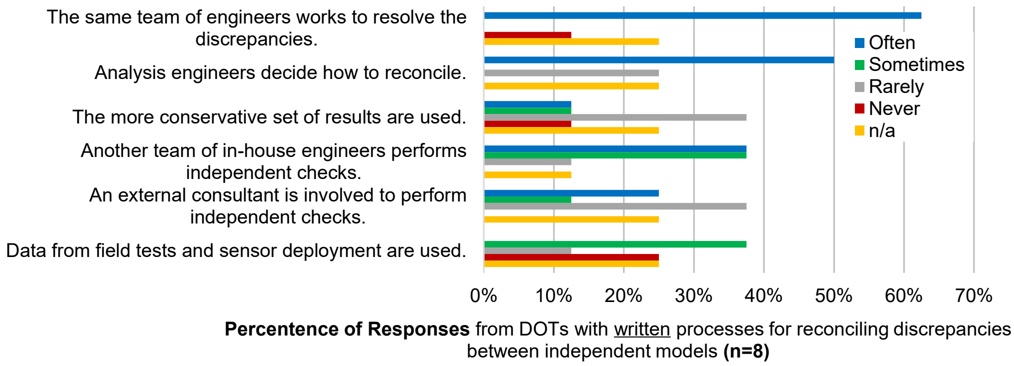

Fig. 13. Methods for reconciling discrepancies between independent models (DOTs with written processes).

3.4 Case examples

Five state DOTs were selected as case examples based on a set of criteria described in Guner (2024). The selected DOTs are as follows: California and Colorado from the West (Pacific and Mountain regions), Louisiana from the South, Iowa from the Midwest, and New York from the Northeast. Some of the findings obtained from these case studies are described below.

The case example agencies use two types of consultant selection processes: project-specific and/or statewide on-call. These agencies require consultants to either submit their QA/QC plans or follow the agency's specific QA/QC plans. As two examples, the Louisiana DOT has a well-defined evaluation and scoring criteria for consultant QA/QC plans while the New York State DOT (NYSDOT) has specific QA/QC plans that the consultants must follow.

All five case example agencies have informal processes that rely on a manager, supervisor, or unit leader to select appropriately qualified engineers based on their experience and availability. This decision also considers professional development needs, including training less experienced engineers or challenging more experienced engineers with unique or interesting projects.

All five case example agencies most frequently use 'one-dimensional line girder analysis.' While all case example agencies rely on the analysis (or design) team to select the most appropriate method(s), NYSDOT provides written guidance on when to use refined analysis methods.

All five case example agencies require a checker to independently verify the accuracy of design engineer's models, calculations, and results. For complex bridges, California DOT (Caltrans) requires project-specific design criteria, a peer review panel, and an independent check conducted by an engineer not associated with the group who has completed the original analysis. Both Caltrans and NYSDOT require the use of different software in the independent check.

To overcome the challenges with finding appropriately qualified engineers in district offices, Caltrans established the seismic and special analysis branch, which is only focused on structural modeling and analysis, while NYSDOT established the Main Office Structures group with sixty-five design staff who only perform structural analysis and final design.

For training engineering staff, Caltrans established a six-week 'bridge design academy' while NYSDOT has a 24-session 'Bridge 101' training series. Iowa DOT indicated the benefits of designer-checker pairing and a dedicated training budget for the professional development of engineering staff.

4. Conclusions

A selection from the major findings are summarized below.

- The majority of DOTs assign more than half (59%) of their new bridge and bridge replacement designs to consultants while they assign almost half (47%) of their existing bridge analyses, including load ratings, to consultants.
- The survey asked three questions on the presence of consultant quality processes. The most common written consultant process, as selected by 61% of DOTs, is 'identifying appropriately qualified consultants,' while the least common written process, selected by only 16% of DOTs, is 'verifying the analysis results obtained from consultants.' The most common 'no process' response, as selected by 37% of DOTs, is the 'bridge analysis models developed by consultants.'
- The survey asked six questions on the presence of in-house quality processes. The most common written in-house process, as selected by 31% of DOTs, is 'modeling a bridge'. The least common written process, as selected by 12% of DOTs, is 'identifying appropriately qualified in-house engineers.' This result is in sharp contrast with the consultant processes where 'identifying appropriately qualified consultants' was the most common written process. The most common 'no process' response, as selected by 41%, is 'validating the analysis software.'

- State DOTs and their consultants most frequently use the ‘one-dimensional line girder analysis.’ The least frequently used method is the ‘nonlinear finite element method.’
- The skills acquired in undergraduate university education may not be sufficient for a competent application of the finite element and strut-and-tie methods and the interpretation of the analysis results obtained from these methods. A qualified training system with standardized requirements could be developed for bridge engineers performing these types of analyses.
- Future research could develop guidance to help state DOTs assess the effectiveness and quality of their QA/QC processes.
- Future research is suggested to develop a nationwide repository for sharing finite element and strut-and-tie models between DOTs.
- Future research could develop guidance and bridge-specific guidance on the development and verification of the finite element and strut-and-tie models.
- New training courses and seminars could be developed to cast light on commonly misunderstood concepts such as verification, validation, uncertainty, error, and calibration, and train bridge engineers on how to effectively perform these activities.

The full details of the studies conducted and the conclusions reached may be found in Guner (2024).

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