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AN ENHANCED APPROACH TO PERFORM SEISMIC-WALKDOWN IN EXISTING NUCLEAR POWER PLANTS

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ABSTRACT

Walkdown is a widely adopted and well-established method to assess the actual state of a Nuclear Power Plants (NPP) and a powerful instrument to identify possible malfunctions of relevant Structures, Systems and Components (SSC) or the robustness of a NPP in case of Periodic Safety Assessment (PSA) studies.

More recently, following the accident at the Fukushima Daiichi NPP from the March 11, 2011 (Great Tohoku Earthquake and subsequent tsunami), additional guidance has been produced to perform such tasks related to seismic events, like in IAEA (2020). Nonetheless, the evaluation of the robustness of SSC remains a challenging task, because it's strongly affected by the experience of the walkdown team and the available NPP data during preparatory works, execution and post-processing of the inspections. Because of this, the (seismic) resistance of a SSC being evaluated during a walkdown according to generic values may differ considerably when compared with a-posteriori assessment (analytical model, qualification data). Sometimes, the selection of a representative SSC for a certain group of components during walkdown may be superseded in a later project stage, because of new findings, information or rankings.

It's in this framework that we propose to implement a comprehensive, interconnected tool to support walkdown teams in their work to improve the efficiency and quality of the assessment. Our article aims to sketch the main features of the tool at a concept stage, and it shows the already achieved advances in Swiss NPPs by means of digitalization. To concretize the overall idea, the paper will address the interface between the civil engineers and other faculties (mechanical, electrical, nuclear safety, etc.); our focus will be on the evaluation of connections built with post-installed fasteners. We will show how data will be collected and stored digitally, as well as an approach to determine fasteners' resistance and connections' demand to obtain Capacity-to-Demand (C/D) ratios. Connections demand estimate will be focused on mechanical equipment (piping supports), but it may be expanded in further stages to other equipment families.

In the last section, the paper will discuss the benefits to combine Probabilistic Safety Analysis (PSA) results with connection resistance quantities (C/D-ratios) to generate a Risk Informed Decision Making (RIDM) platform. The goal is to provide guidance to engineers and walkdown teams highlighting the most important critical connections during the assessment process.

INTRODUCTION

General Considerations

Advances in computer science and the development of tailored software are contributing to the expansion of digital tools like Building Information Modelling (BIM) in the nuclear industry. In line with this evolution, we sketch in the following the concept for a tool able to support the work of walkdown teams in NPPs. Our primary goal is a consistent, objective and safety-oriented allocation of the available resources and improving the quality and efficiency of walkdowns.

Interface between Civil Engineering and Other Faculties

The connection between mechanical and electrical equipment and the reinforced concrete structure represents one of the most common encountered interface problems between different faculties in a NPP. Because connections are the link between the primary structure and secondary system/components, their design construction and operational performance is of eminent importance during several Plant Operational State (POS) and transient conditions (anomalies, accident or extreme events).

Typically, in each NPP thousands of systems and related equipment are mounted to the primary structure with post-installed fasteners, pertaining to the original construction time of the NPP or being installed more recently during modernization projects (Figure 1). Consequently, a large heterogeneity in the qualification, design and construction criteria of such fixations exist. To perform efficient, integral re-assessments according to today's state-of-practice, a dedicated tool able to collect connections' data is needed.

Figure 1. Examples of connections with post-installed fasteners (left) and density of SSC inside a reactor building in an existing NPP (right)

To overcome time-expensive preparatory work and ensure acceptance, the new tool must take advantage of today's digital tools, provide interconnectivity between databases and abilities in visualization. This, because in existing NPP many plant data are stored in an Information Management System (IMS), but such information is poorly interconnected together. A major tool's advantage should be to link equipment's data pertaining to a specific connection: system classification and design requirements, system general data, location and so on. Particular attention must be dedicated to guarantee the actuality of the equipment data (avoid the use of superseded parameter).

To achieve the afore-mentioned goals, the capabilities of Building Information Model (BIM) as a data management tool (planning, operation) as well as in-the-field (construction, walkdown, inspection) will be used. According to our experience, considerable time-effort is needed in developing a functional, comprehensive BIM for an existing industrial installation, however, the final product has the potential to reduce the time-effort of routinely, repeatable or assessment tasks over the years – especially from an owner's perspective.

DIGITAL BUILDING MODEL

Starting from the existing construction drawings, a detailed 3D model of the structure is generated in a BIM-compatible software to represent the structural elements; additionally non-structural elements like partition walls, secondary steel structures, etc. may also be implemented. To verify the correctness of the 3D model with the reality, a laser-scanning campaign (point cloud) and 360° pictures must be collected for

the entire building and cross-checked with the developed model; after passing this quality assurance process, the building model is ready for further applications.

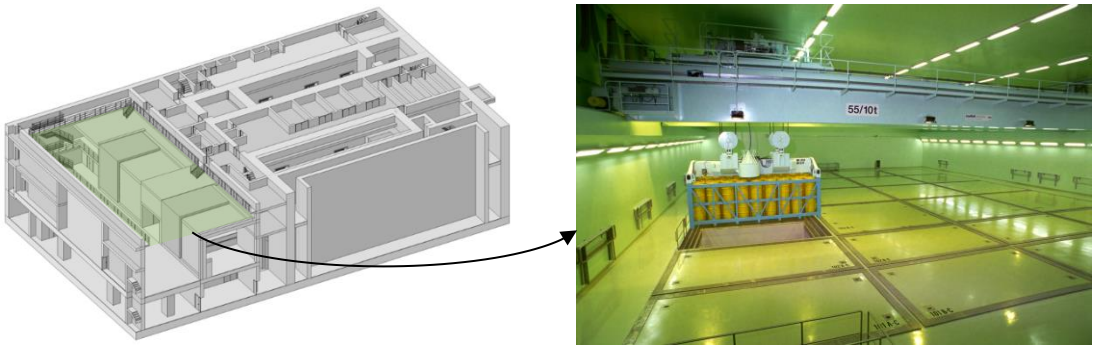


Figure 2. Grade of detail in a 3D digital model (left) and comparison with the reality (right)

A first enhancement consists of implementing the existing post-installed connections in their location (floor, wall, ceiling, column) and overlap the collected data of the laser-scan campaign, the 360° pictures and the already developed 3D digital model. By doing this, the 3D model enables stakeholders to get an overview of the position, number, dimensions and kind of connections mounted into the building.

Figure 3 shows how a connection is detected with 360° and point cloud and subsequently placed into the 3D building model. In contrast, Figure 5 displays how the 3D model looks like when several connections are modelled.; by selecting on a connection (red), a separate window will open and list the available parameters (type of anchors, dimensions, construction protocols, etc.).

If new systems or components should be mounted, the 3D building model, the laser-scanning and the 360° pictures provide useful information: the existing plant layout and the possible conflicts with other SSC are detected in advance, reducing time-consuming inspections, exposure to radiation and enabling project optimization between the different faculties. BIM-based approach has already been implemented with success and satisfaction of the different stakeholders in pilot projects carried out in the last years in Swiss NPPs (see Figure 4). BIM has also been implemented in the design and execution (BIM-to-Field) of two new structures at Beznau NPP since 2023, providing useful lessons-learned to the application of this technology.

Figure 3. 360° picture (left) and point cloud of wall-mounted connection (right) as well as check of the correct dimension and positioning in the 3D model (red area of the connection)

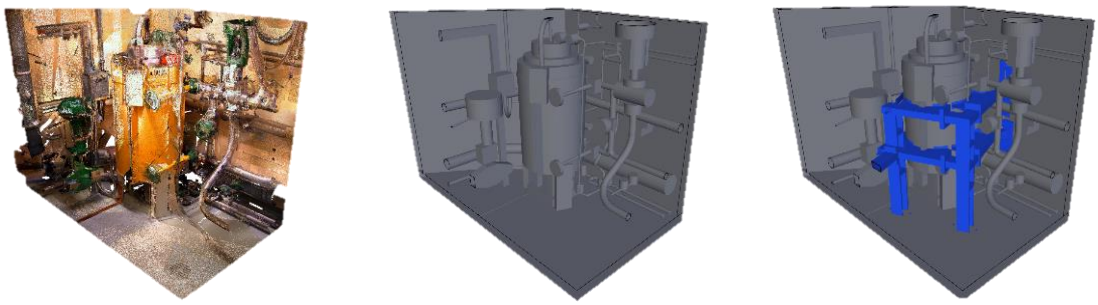


Figure 4. Example of the in-situ data collection of a component with point cloud and 360° pictures (left), implementation in Autodesk Revit (mid) and virtual testing of a new steel structure at design stage (right)

To streamline the data acquisition of several hundred of connections in a building a dedicated application has been developed and tested; therefore, a systematic, efficient and comprehensive data collection for further application is ensured. According to our experience, five up to ten minutes may be necessary to collect data and take pictures of the connection (also store in the database).

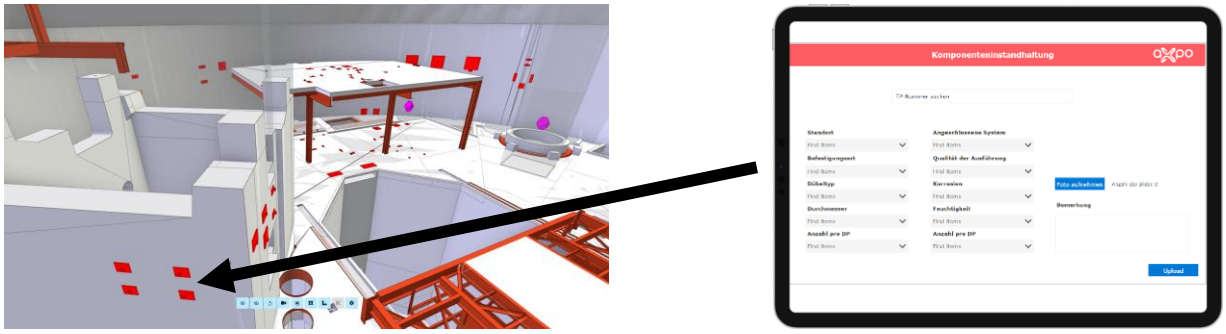


Figure 5. 3D model of a nuclear structure and location of post-installed fasteners (left, colour red) as wells as example of specific data collection (right)

After completion of the data collection, several statistics may be provided such as: fastener-types, dimensions, heatmaps, or 3D visualizations (Figure 6). Further, interconnectivity between databases enables the identification of correlations otherwise not easily identifiable. The quantification of connections per room, building, or fire section may also be a useful information for some applications.

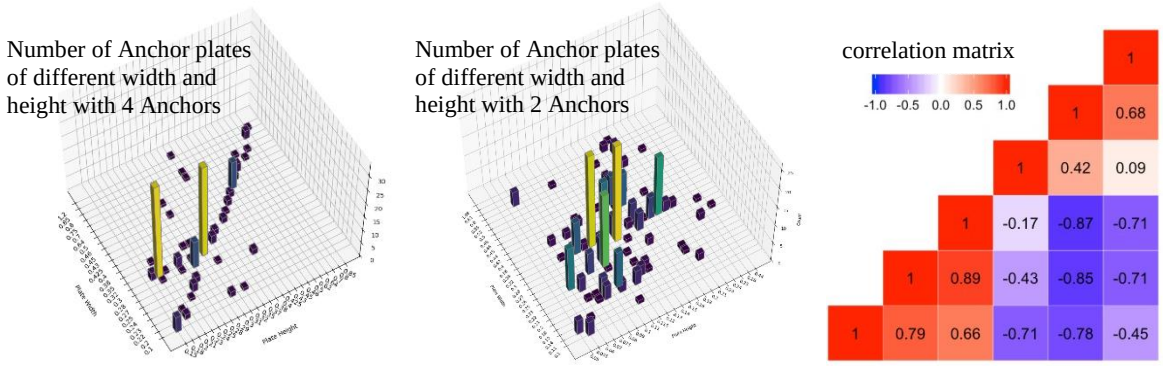


Figure 6. Examples of 3D columns of Anchor plates in relation to their dimensions; diagonal values mean quadratic plates and the column's height is the number of plates in the database

CAPACITY AND DEMAND ESTIMATE FOR POST-INSTALLED FASTENERS

A further enhancement of the tool may be achieved when the connection's capacity and demand as well as Risk Important Measures (RIM) arising from a Probabilistic Safety Analysis (PSA) are interconnected and convolved together to rank the connections according to safety principles.

Capacity of Post-Installed Fasteners

Capacity of post-installed fasteners may be estimated using commercial or user-defined software, able to automatically read the parameters of the connection's tool and combine it with other data. Connection's capacity may be computed for different concrete cracked conditions (0.3, 0.5 or 0.8 mm), according to standards (SIA, Eurocodes) or NPP-specific guidelines (GSKL). Axial-Shear-Bending-Interaction diagrams (Figure 8) provides an effective representation of the connection's resistance or may be used for sensitivity studies (comparison of the results for different parametrical assumptions).

A particular effort has been made by Swiss NPPs to estimate the capacity of fasteners according to today's state of knowledge, even if these elements were in commercial use several decades ago (since 1960's) and were qualified according to superseded assessment methods. A major contribution to reliably estimate the capacity of such fasteners in cracked concrete were data obtained by shock loads experiments carried out by the Swiss Federal Office for Civil Protection (FOCP) as shown in Figure 7.

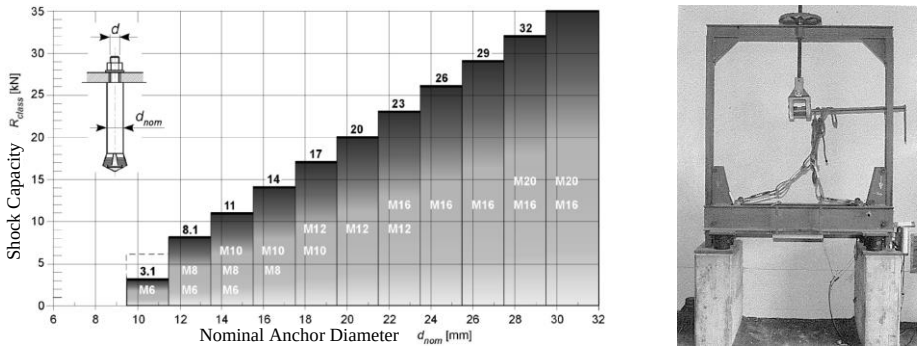


Figure 7. Typical fastener shock resistance R_{class} as a function of diameter (left) and FCOP set-up used for tension capacity experiments in cracked concrete (right)

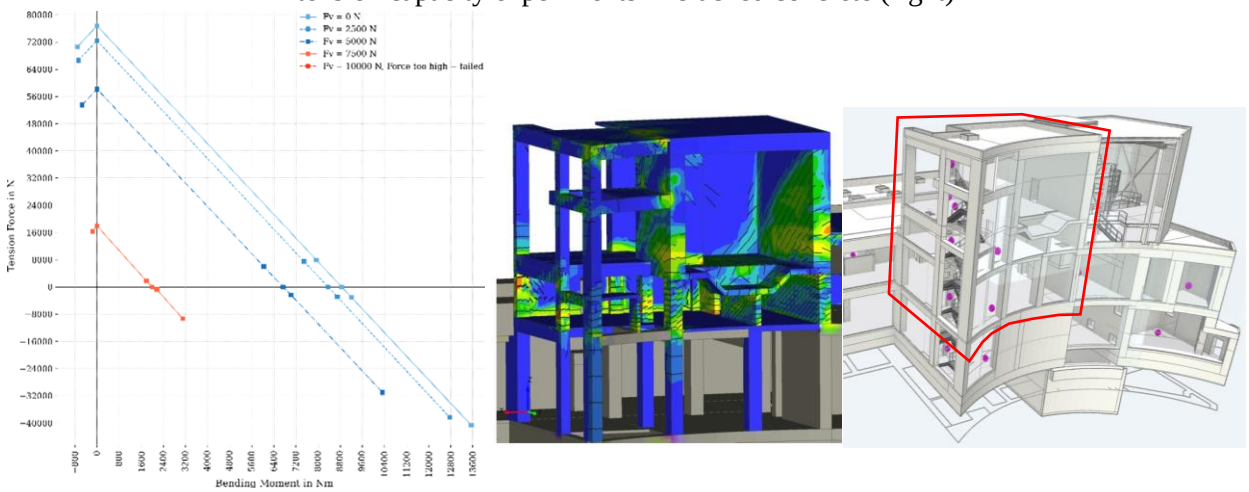


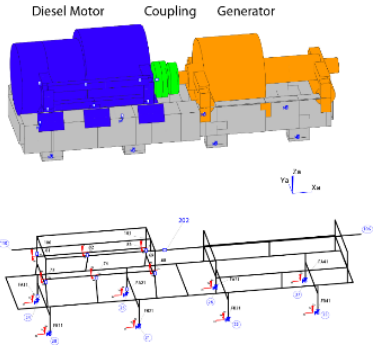
Figure 8. Example of capacity diagram for 2 x 2 connection plate with post-installed fasteners and cracked concrete with crack width 0.5 mm (left), crack map (mid) and BIM model (right)

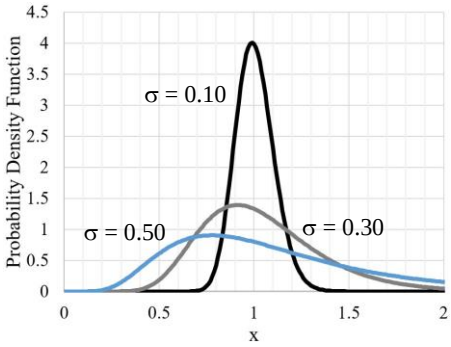
Concerning the consistency of the concrete cracking assumption with the considered event (i.e. earthquake), new improvements are expected in the next years. As an example, Swiss NPP are working on the implementation of crack maps coming from detailed, dynamic analyses into BIM environment and their visualization by means of Augmented Reality (AR).

Methods to Estimate Connection's Demand

Connection's demand may not be easily available, especially if the design assumptions aren't available or superseded loads were used (i.e. earthquake). To overcome this problem, we propose alternative ways to predict the expected Building Connection Loads (BCL) for the desired event. The methods differ in the level of effort and detail; therefore, the combined uncertainty of the BCL must be defined accordingly, i.e. $\sigma = 0.1$ if a structural analysis is available or $\sigma = 0.5$ if generic data are used.

Structural model of a motor, generator and coupling to estimate BCL.





PDF (normalized) of BCL in accordance with the method used to estimate connection's demand

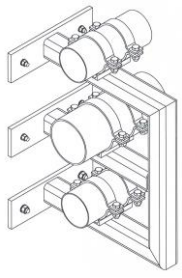
Figure 9. Example of an analytical model for a diesel generator (left) BCL uncertainty distributions (right)

To estimate the BCL for several hundred connections, we may adopt a graded approach that saves time and financial resources, focusing subsequent effort to high-risk connections: in other words, we do not need to achieve a high level of accuracy for BCL with low-risk connections.

Connection's probability of failure

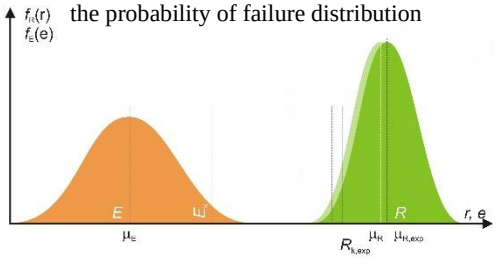
Obtaining C/D-ratios and considering aleatoric and epistemic uncertainties, a probability of failure distribution reflecting the level of accuracy and prediction for each item is obtained. This may be used as a starting point for the convolution with RIM; according to particularities in Swiss NPPs, we propose to initially estimate C/D-ratios for normal operation condition and seismic events (10^{-3}/y resp. 10^{-4}/y).

Demand

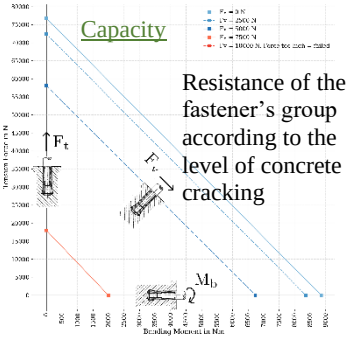


Building Connection Load (BCL) according to the considered event

Distribution of the BCL (demand) and connection's resistance to obtain the probability of failure distribution



Capacity



Resistance of the fastener's group according to the level of concrete cracking

Figure 10. Example of the convolution of connection's demand and capacity to obtain C/R-ratios

ADDITIONAL CONSIDERATIONS ON THE DEMAND ESTIMATE

Of course, to estimate the demand a design documentation is preferable, but not always available, especially in the case of new load provisions. Here we provide some advice based on experience, to possibly constrain the level of effort. A typical categorization of mechanical and electrical systems and components in a Swiss NPP according to different classification methods is shown in Figure 11.

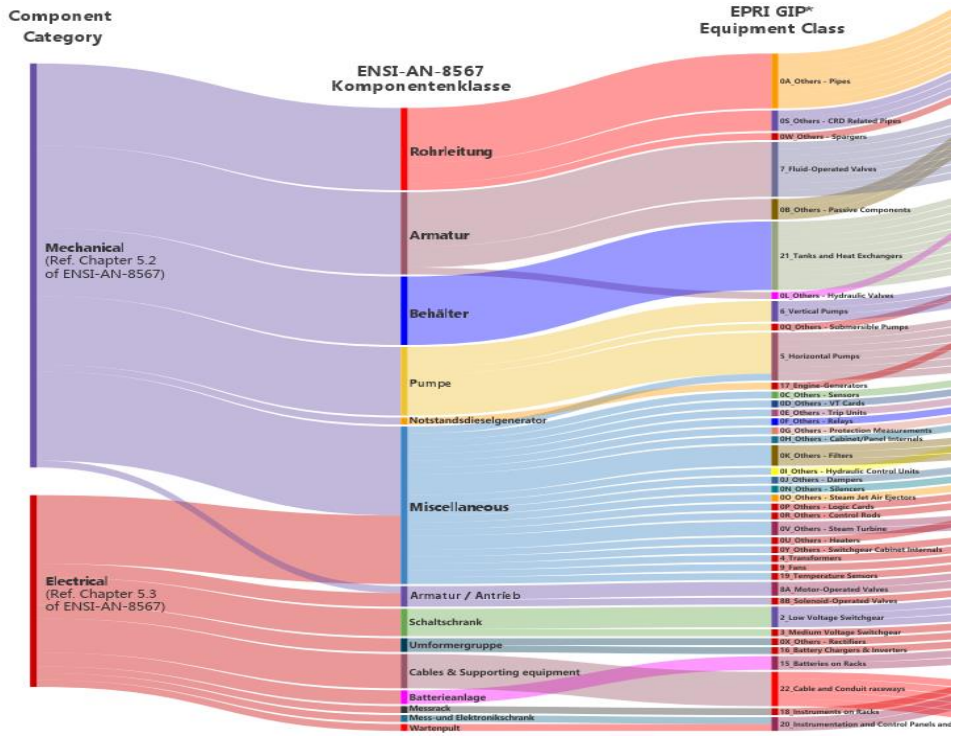


Figure 11. Example of Sanky-Diagram of the Seismic Equipment List (SEL) for an existing Swiss NPP

Demand on Electrical systems and components

Electrical equipment like cabinets, racks, cable trays, batteries, etc. are generally easy to handle from a structural perspective, because BCL is mostly governed by a low number of parameters like mass, dimensions, support layout or distance, frequency range, location; simplified approaches are in those cases fairly accurate. Furthermore, large datasets from previous analytical models may be post-processed in the future to gain additional insights and accurate predictions based on a few indicators (correlation matrix).

Demand on Mechanical systems and components

BCL of several mechanical equipment (pumps, tanks, etc.) may also be estimated with simplified approaches. Mechanical pipe systems, however, often extend over several rooms, floors and buildings and may be in their nature complex (Figure 12). If BCL based on an analytical model isn't available, following information should be collected: design parameter (pressure, temperature, pipe dimension and wall thickness), support spacing and data on heavy installation parts (e.g. valves, fittings). A general approach may be the development of a plant specific Installation Guideline (IG), as extensively exercised in German NPPs. By means of the span width between the pipeline brackets, the support loads and subsequently the BCL can be roughly (!) estimated – the procedure is sketched in Figure 13. Of course, a fundamental understanding of the piping support concept remains an essential requirement in such cases.

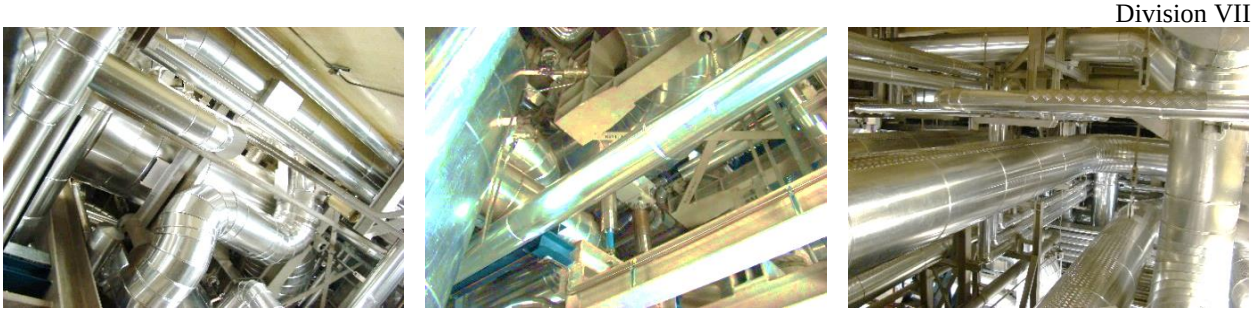


Figure 12. Example of complex pipe systems in a Nuclear Power Plant

Figure 13 (center) also proposes an alternative way to determine BCL demand of pipe system supports. By collecting existing calculation data of several pipe system and support proofs and analyze them systematically, estimated mean values and variances of BCL can be obtained with respect to pipe measures, design data and Earthquake demand.

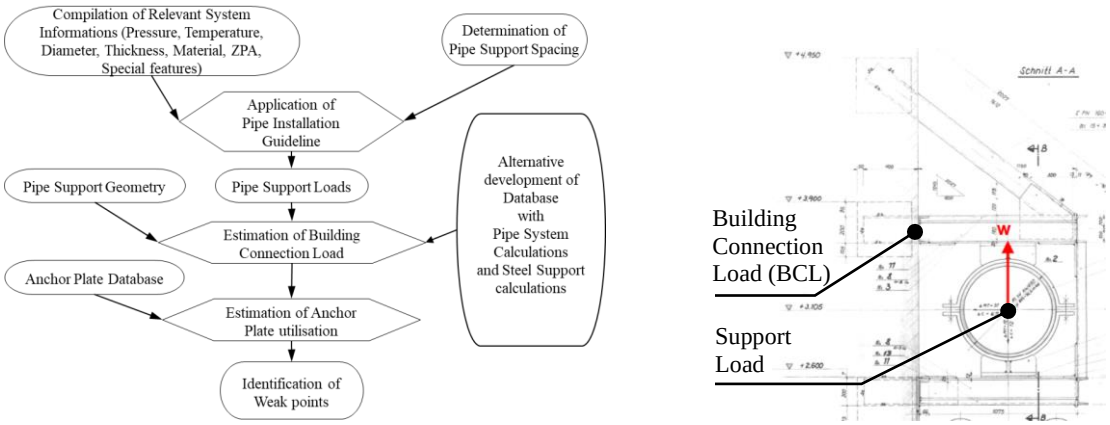


Figure 13. Diagram for the estimate of BCL and weak points (left) as well as definitions (right)

Proof of Concept on the use of Artificial Intelligence and Machine Learning

Promising methods may also be based on the use of Artificial Intelligence (AI) and Machine Learning (ML) as already tested for other civil engineering applications, i.e. in Proske (2023), Güner (2024). To investigate the grade of precision and accuracy in BCL prediction, the use of Convolutional Neural Network (CNN) will be tested to mechanical pipe systems; to this extent, the available datasets of several analysed pipe systems, combined with the point clouds and 360° images will be post-processed to train the predictive model and extract the desired values. A proof of concept will start this year in a Swiss NPP to test the pros/contras and gain lessons learned of such applications.

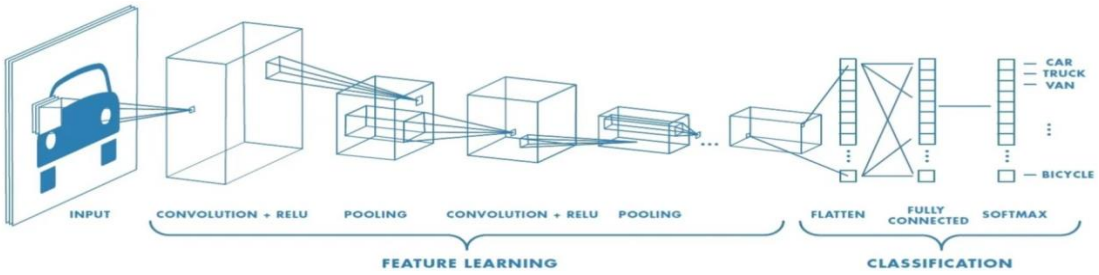


Figure 14. Convolutional Neural Network (CNNs) with many convolutional layers (MathWorks)

RISK INFORMED DECISION MAKING (RIDM)

Previous steps in this paper should be used to obtain a Risk Informed Decision; this does not only mean to consider the failure probability of a component but also the consequences of such the failure for the entire plant. For connections this means the consideration of the failure of the mounted system or components; in other words, the failure of the building connection yields to the complete failure of the joined systems and the consequences for the cooling path of the plant. Therefore, two connections with a similar failure probability may be ranked far away from each other (see Figure 15) if the consequence of the connected systems are diverging.

In PSA models, two of the most used Risk Importance Measures (RIM) to rank SSC are the Risk Achievement Worth (RAW) or Fussel-Vessely Importance (FV):

- the RAW measures the "worth" of a given basic event in achieving the present risk level (probability of undesired consequence in the following), by considering its maximum that is when the basic event always occurred. It indicated the importance of maintaining the current level of reliability for the basic event *i*.
- the FV is the fractional contribution of a given basic event to the probability of the undesired consequence when the basic event probability is changed from its base value to zero (i.e. the basic event never occurs) or equivalently the (conditional) probability that at least one "minimal cut set" containing the basic event occurs (given that the undesired consequence is occurred). Referring to an individual basic event, the FV measure is defined as:

$$FV_i = \frac{f - f(P_i = 0)}{f} \approx \frac{f\left(MC_{including\ i}\right)}{f} = \frac{a \cdot P_i}{a \cdot P_i + b}$$

$f(P_i = 0)$ is the probability of the undesired consequence when the basic event probability is zero

The above-mentioned RIM may be extracted for the desired POS (typically Full-Power) and initiating event according to the Level 1 PSA for each SSC modelled. Because the connection tool contains information to the mounted system (i.e. system ID, room number, etc.) such RIM can be linked to each item and deliver the result showed in Figure 15. Fig. 15 right shows the robustness of the results for a large number of components. It is worthwhile to note that especially the components with very high and very low risk ranks show a very stable result in the ranking.

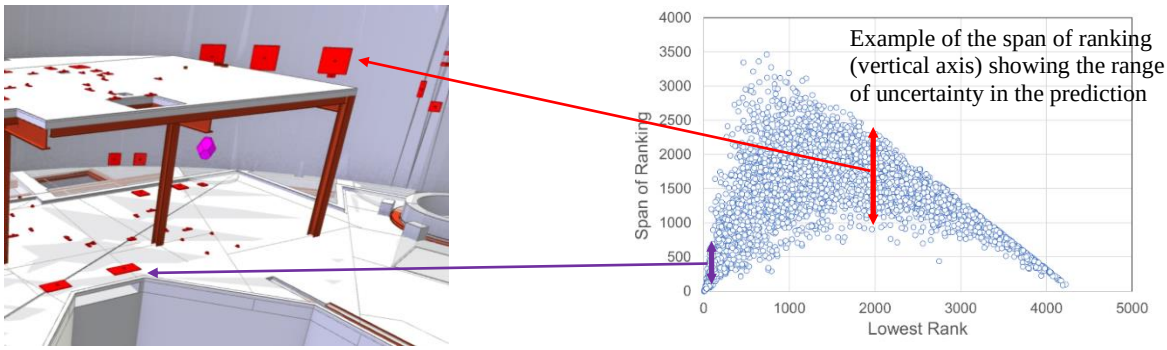


Figure 15. Classification and visualization of each connection according to the lowest ranking (risk) and span of ranking (uncertainty) as a RIDM tool for the desired POS and event (i.e. earthquake)

The outcome will be a Risk Informed Decision Making (RIDM) tool for connections that it's implemented in BIM and supported by AR, to facilitate the general understanding. Such a tool is not only providing guidance to walkdown teams but it's also very effective in a) highlighting high-risk connections, b) identify

potential interactions between low- and high-risk connections in a specific area, c) understand and verify the spatial correlation of assumptions made in a PSA d) allocate resources to the risky connections in a specific area. RIDM applications may range from aging-management to monitoring, periodic safety-assessment or Long-Term-Operation projects.

OUTLOOK AND CONCLUSION

This paper drafts a concept to improve the interconnectivity of available information in a NPP and their possible application to interface tasks between civil engineering and other faculties; focus has been set to connections with post-installed fasteners to concrete, because of major importance to guarantee the functionality of mounted electrical and mechanical equipment during operation or accident conditions in Nuclear Power Plants.

To this extent, the capabilities of Building Information Model (BIM) as a data management tool (planning, operation) as well as in-the-field (construction, walkdown, inspection) are used. A major benefit of the method consists in the integration of features from different faculties in a single model. The proposed Risk Informed Decision Making tool is a first attempt to support walkdown teams as well as engineers during, maintenance, aging-management, periodic safety analysis or modernization projects and give them guidance. We believe that the digital tool will a) reduce time-effort to collect basic documentation and complete technical evaluations, b) improve the interaction between stakeholders, c) guarantee an efficient allocation of technical resources.

Next steps consist in the elaboration of the different tasks, the testing and the implementation in existing NPPs as well as the training of the stakeholders.

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