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Numerical Model Development of Reinforced Concrete Beam for Structural Health Monitoring

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ABSTRACT

Reinforced concrete (RC) structures are used in various engineering projects of all sizes and shapes. In order to maintain its safety and serviceability, it is necessary to evaluate the durability of an existing structure by conducting structural health monitoring. Thus, the main problem of this study is the lack of inspection, and no predictive maintenance is performed in the existing structure because the conventional method of structure monitoring needs a high cost to execute. Therefore, it will cause structural deterioration and lead to structural failure. In this study, a numerical model of RC beam was developed by using Finite Element Software. The research objective is to validate the real experimental work by using numerical model of RC beam in Marc Mentat software and investigates the potential of the numerical model development for structural health monitoring. In order to achieve the objectives, Marc Mentat software was used to develop a numerical model of RC beam, which validates the results based on the previous experimental work. Next, the qualitative data were collected through an interview session with several experienced Engineers and Project Managers to investigate the potential of the developed numerical model. The collected data were analyzed by executing content analysis and represented in the form of a matrix table. It is found that the numerical analysis produces the same tendencies as previous experimental results. So, the numerical model could validate the experimental work with no significant difference. Moreover, all the respondents agreed that this numerical approach has the potential to be implemented in the structural health monitoring work. This study suggested an alternative method of monitoring the structural conditions. This numerical method promises precise data in real-time with a minimum cost and time compared to the conventional method.

1. Introduction

The increasing demand for reliable Structural Health Assessment (SHA) has spurred the development of Structural Health Monitoring (SHM) as an integral part of the construction

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monitoring phase. SHM plays a crucial role in enhancing the safety and maintainability of critical structures. It allows for the monitoring of real load conditions and provides insights into structural performance on-site. These capabilities improve the safety and usability of structures, ensuring they function properly over their long service lives and are protected against major collapses in the event of serious occurrences. SHM provides real-time and accurate information about structural health conditions [1], enabling the prediction of future accidents and estimation of a building's lifespan.

The advancement of SHM is driving the adoption of modern technologies. As the method for evaluating structures becomes increasingly digital, industries are transitioning towards digitalization, prompting experts to advocate for the integration of IR4.0 technology within the context of the Internet of Things (IoT) manufacturing and intelligent structures. This integration has given rise to the field of SHM, which emerges from the intersection of advancements in various engineering disciplines with civil engineering. The IoT is leveraged for SHM, and systems developed within this framework have demonstrated promising results [2]. These systems primarily serve to monitor different parts of public or industrial structures, mitigating the risk of unexpected collapses.

However, ineffective implementation of SHM can result in degradation and damage throughout the service life of structures. Continuous exposure to environmental factors inevitably leads to deterioration, such as corrosion and fatigue, in building structures [3]. This highlights the importance of deploying SHM effectively to maintain the integrity and longevity of structures. Past research on the development of numerical model in implementing the SHM is limited. The development of numerical model is not only saving the time and cost, but also ensure the quality of work while parallel with the sustainable development goal in IR4.0 era.

1.1 Research Background

Reinforced concrete (RC) structures are widely employed in engineering due to their ubiquity and significance [4]. The contemporary demand for such buildings underscores the necessity of preserving their structural integrity [5]. Among the components of concrete structures, the RC beam is particularly susceptible to degradation [6]. Extensive scientific research has been conducted, focusing on the deterioration of RC beams caused by chemical and mechanical forces, notably corrosion. Real-time monitoring of all load variations, environmental factors, and reactions is imperative, as periodic maintenance alone cannot achieve this level of oversight [7]. Neglecting regular monitoring and maintenance can lead to rapid deterioration in concrete structures. Failure to conduct regular monitoring and maintenance can result in cumulative impacts, including accelerated degradation of a building's structure and finishes, as well as adverse effects on its contents and occupants [8]. The conventional monitoring approach entails significant maintenance costs, and the increasing complexity of concrete structures presents challenges for inspections.

Conventional methods for accessing specific areas within a structure are both costly and hazardous, making it challenging to assess their condition effectively [9]. This process requires skilled personnel, specialized equipment, and a significant amount of time. Structural assessment should encompass various components, including beams, columns, and slabs, primarily through visual inspection. Despite the emergence of non-destructive assessment (NDE) as a technology for structural inspection, its application to concrete structures is still underdeveloped [10]. Additionally, common NDE procedures can be challenging, expensive, or unreliable due to the complex nature of concrete structures.

Numerous factors influence the durability of concrete structures, including chemical reactions driven by parameters such as cement type, concrete cover, casting technique, curing procedure, and other implementation conditions, all of which directly affect the concrete's lifespan [6]. Additionally, mechanical variables, such as high load-bearing on the structure, contribute to the deterioration process, incurring substantial costs for its control. Addressing this challenge can be facilitated through the implementation of a numerical model, as the simulation response is primarily contingent on how effectively the structural behavior of the material is represented in the software. Numerical simulation methods are utilized to assess real-time experiments using analytical models with modern software. Previous research has concentrated on the analysis and numerical modeling of a concrete slab to investigate structural failure, employing non-linear analysis and three-dimensional computational models to propose a practical solution [11]. Therefore, numerical models offer a viable approach to mitigating this problem.

1.2 Problem Statements

Monitoring the response of building structures is crucial for maintenance purposes, but conventional methods are often prohibitively expensive. These costs include the utilization of modern technology for on-site monitoring, especially for large structures like long bridges and skyscrapers that exceed standard design geometries [8]. These assumptions must be validated through on-site monitoring using advanced technology. Monitoring also helps determine when maintenance is needed, requiring real-time data collected over several years. Experience from other states suggests that maintenance of building structures to protect them from deterioration over the next decade can cost between 20 to 30 years' worth of maintenance expenses [7]. Prolonged monitoring periods will lead to increased maintenance costs, further compounded by the need for qualified personnel, such as structural engineers and contractors, to carry out the monitoring and maintenance procedures [8]. Resolving this issue is crucial to avoid exorbitant maintenance costs.

Additionally, there is often a lack of monitoring and predictive maintenance due to cost constraints from clients. This lack of monitoring can result in the degradation and eventual collapse of the building structure. Without proper maintenance, buildings age prematurely, leading to deterioration and potential collapse [12]. Structural Health Monitoring (SHM) systems have been developed and tested successfully, focusing on monitoring building structures to reduce the risk of injury from sudden collapses [2]. Structural failures can lead to tragedies, not only in terms of human and economic losses but also in terms of future social and psychological consequences. However, conventional methods for predicting maintenance can be challenging, especially when accessing difficult-to-reach areas [13]. Implementing technology-based monitoring methods can help prevent sudden structural failures.

To address these challenges, a numerical model has been developed as an alternative to conventional methods. This model aims to reduce maintenance costs while maintaining the accuracy of results during structural health monitoring. The potential of this numerical model development for structural health monitoring in the construction industry is being investigated.

2. Literature Review

2.1 Construction Overview

2.1.1 Structural health monitoring

Over the past few decades, Structural Health Monitoring (SHM) has evolved into a critical practice for evaluating the condition of buildings, regardless of their maintenance status, with the primary objective of ensuring structural safety. SHM is specifically designed to monitor the loading environment and structural response, thereby enabling the assessment of safety and the identification of potential operational incidents and damage [7]. This proactive approach helps to maintain the structural integrity of buildings over an extended period.

Concurrently, Structural Health Assessment (SHA) monitoring is conducted during the operational phase of buildings to track their condition and determine the necessity for repairs. The implementation of SHA monitoring during the service life of buildings is essential for assessing the structural health of buildings in real-time, identifying any potential issues, and ensuring that they are promptly addressed to maintain structural integrity and safety.

In essence, both SHM and SHA monitoring play integral roles in ensuring the long-term structural safety and integrity of buildings. These monitoring practices are essential components of a comprehensive maintenance strategy aimed at preserving the functionality and safety of buildings throughout their service life.

2.1.2 The technology used in SHM

Structural Health Monitoring (SHM) aims to create an automated system that can continuously monitor, inspect, and detect structural issues with minimal human intervention. Previous studies have employed Wireless Sensor Networks (WSNs) to collect data from diverse sensors mounted on structures. This data is subsequently analyzed to extract meaningful insights regarding the structure's current state and to assess its maintenance requirements and safety considerations [14]. Table 1 provides an overview of several studies that have explored the use of technology for structural health monitoring.

Table 1
Reviewed of technology used in SHM

No.	Type of structure	Technology	Measure parameter
1	Steel structure	Piezoelectric sensors	To identify the deformation and stress [15]
2	Concrete building	Numerical simulation	Dynamic behavior of buildings [16]
3	Heritage building	Piezoelectric accelerometer	Carried out real-time monitoring and FEM [17]
4	Heritage structure	Numerical simulation	Static and dynamic response of the building [18]

In conclusion, various modern methods are employed in SHM, each possessing its own set of advantages and disadvantages. While these methods contribute significantly to assessing the condition and integrity of structures, there is room for further refinement and enhancement in SHM practices. Therefore, in this research, a numerical model will be developed to advance and innovate the method of structural health monitoring. By leveraging numerical modeling techniques, this approach aims to overcome limitations and improve the effectiveness and efficiency of SHM, ultimately enhancing the safety and longevity of structures.

2.1.3 Challenge in structural health monitoring

In contemporary construction practices, the lack of predictive maintenance during the construction monitoring phase is a notable issue, primarily due to significant disadvantages associated with conventional monitoring methods. Extensive studies have explored this limitation, identifying six key challenges in the construction monitoring phase, which can be categorized into two main areas: management issues and technical problems.

One major challenge is the financial issue, as there is often a lack of allocated budget for monitoring and maintenance activities, limiting the implementation of effective monitoring strategies. Additionally, inadequate supervision from the maintenance team can lead to ineffective monitoring practices and missed opportunities for preventive maintenance. The shortage of qualified engineers and specialists proficient in structural health monitoring also hinders the implementation of effective monitoring programs.

Furthermore, insufficient training and motivation among maintenance staff can result in suboptimal monitoring practices and reduced effectiveness in identifying potential issues. The absence of specialized software tools for monitoring and maintenance further complicates matters, impeding the efficient collection, analysis, and management of monitoring data. Lastly, inadequate implementation of preventive maintenance measures can increase the risks of structural issues and failures [19].

In summary, these challenges underscore the need for comprehensive strategies to address them effectively and ensure the long-term structural health and integrity of built environments. Table 2 provides a summary of the challenges in SHM identified in this research, highlighting the multifaceted nature of these challenges and the need for comprehensive strategies to address them effectively.

Table 2
Challenge in SHM [19]

Item	Challenge	Description
1.	Management i. Financial ii. Lack of Supervision from the maintenance team iii. Lack of engineer and specialist iv. Lack of training and motivation	Maintenance costs exceed budget estimates throughout the year. Supervisors perform work without proper training and preparation. Lack or no manpower available for some of the work that needs to be done. No proper training course related to the maintenance.
2.	Technical i. Lack of maintenance software ii. Failure of preventive maintenance	No updates or upgrades were made to existing systems that required maintenance. No preventive maintenance is done because the cost is too expensive.

Furthermore, there are five significant challenges in the monitoring phase that must be addressed. The first challenge pertains to large-scale structures, which present unique monitoring complexities. The second challenge is the vast amount of data produced during monitoring, requiring efficient management and analysis strategies. Additionally, site conditions pose challenges, as access to certain areas for monitoring purposes can be difficult. Moreover, uncertainty and reliability are critical issues in ensuring the accuracy and effectiveness of monitoring efforts. Lastly, the most significant challenge in structural monitoring is cost, encompassing the entire expense of monitoring operations [20]. Consequently, while the first author identifies six challenges, the second author lists five. Table 3 provides a summary of the challenges in SHM as identified in this research.

Table 3
Challenge in SHM [20]

Item	Challenge	Description
1.	Large scale structure	Structures such as long bridges and large dams are critical from a commercial and service standpoint.
2.	Huge data produce	Monitoring generates a lot of data. There are so many sites to monitor and so much data to collect.
3.	Site conditions	The structure is hard to access due to the structure's location as a construct and environmental factors such as speedy wind or heavy rainfall.
4.	Uncertainty and reliability	To determine the actual structural reliability of the monitoring data.
5.	Cost	Cover the entire cost of monitoring operations.

In conclusion, the primary challenge in building structure monitoring is cost. This is because nearly all issues in SHM are related to costs, whether in terms of management, technical issues, or other related aspects.

2.2 Structural Deterioration
2.2.1 Structure deterioration phase

There are three distinct phases that precede structural deterioration. The first phase, known as Predictive Maintenance (PdMP), involves the owner incurring fixed annual maintenance costs to evaluate the condition and strength of the building, alongside installing systems on the structure. Subsequently, the Reactive Maintenance (RM) phase ensues, characterized by undetected structural deterioration, which only becomes visible towards the end of this phase. Finally, the Replacement Phase (RP) occurs, marked by a rapid overall deterioration of the structure, leading to repair costs surpassing the expense of total replacement [21]. This progression is graphically depicted in Figure 1, illustrating the relationship between repair costs and time.

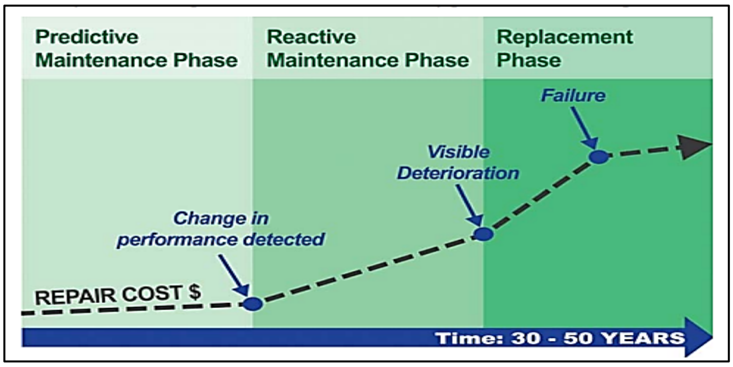


Fig. 1. The graph of the cost of repair versus time [21]

2.2.2 The Factor of structure deterioration

Corrosion in reinforced concrete poses a significant challenge, leading to structural and infrastructure deterioration. The corrosion of reinforced steel, especially in harsh environments such as those rich in chloride ions from saltwater or deicing chemicals, is a major contributor to structural degradation [22]. Environmental factors play a crucial role in initiating corrosion, typically starting with the presence of moisture and oxygen in the environment. Rebar corrosion occurs when the level of chloride ions on the steel reinforcement surface exceeds a certain threshold. Initially, this process reduces the cross-sectional area of the steel reinforcement, followed by an increase in the volume of corrosion material, exerting pressure on the concrete surface. Research has outlined a three-stage corrosion process in concrete, starting with the depassivation of the reinforcement, followed by corrosion production and extensive stress on the concrete surface. The final stage marks the onset of structural deterioration [6].

Furthermore, building deterioration is often attributed to dampness, which has a profound impact on structures. Moisture can lead to hazardous conditions, causing severe cracks not only on the plaster surface but also within the concrete [23]. Additionally, studies have shown that acid rain contributes to building structure deterioration, exposing the structure to alternating wetting and drying cycles [24]. In summary, two studies have highlighted humidity in the environment as the primary factor contributing to structural deterioration.

2.3 Previous Research on the Strength Prediction of Existing Structure

The prediction of structural strength is a critical aspect of ensuring the safety and reliability of building structures, and it has been a focal point in structural health monitoring (SHM) research. Various technologies are employed to make these predictions, aiming to prevent failures in building structures. Previous studies have demonstrated the effectiveness of prediction methods, such as the prediction of shear strength in reinforced concrete (RC) beams using finite element analysis [25]. This research introduced a new approach for performing displacement control analysis to determine the ultimate shear strength of structural components under distributed loads. The study compared the shear strength of RC beams subjected to evenly distributed loads with those subjected to concentrated loads at the middle of the span. The results showed that the shear strength of the critical section of beams subjected to distributed loads was 76% stronger than that of beams subjected to concentrated loads. The study also compared the predictions of shear strain in longitudinal rebar made by the American Association of State Highway and Transportation Officials (AASHTO) specification and the ACI318-14 code with the results of finite element method analysis, showing a 19% discrepancy.

Another study investigated the effect of hollow sections on the strength of foamed concrete beams using 30% processed spent bleaching earth (PSBE) as partial cement replacement [26]. The study compared the deflection of specimens with theoretical values and investigated the mode of failure. The study also verified the analysis using Finite Element Method (FEM) software ANSYS, modeling a beam and comparing the results with laboratory experiments. The maximum difference between the experimental and predicted results for flexural strength was found to be only 6.31%, indicating good agreement between the two.

Additionally, a numerical study developed a model for predicting the structural response of composite Ultra-High-Performance Concrete (UHPC) – concrete members considering bond strength at the interface [27]. The study used a finite element (FE) model to predict the structural behavior of reinforced concrete members reinforced with UHPC, modeling concrete damage in LS-DYNA. The model was calibrated and validated using experimental data, and a new approach based on equivalent beam components was developed for the interface between UHPC and normal strength concrete (NSC) substrate. The FE model effectively predicted the structural reaction of UHPC concrete composite components with good accuracy.

In conclusion, previous research has extensively explored the prediction of strength in existing building structures, demonstrating the accuracy and reliability of these methods. Therefore, the development of numerical models for reinforced concrete beams in SHM applications is a viable and valuable approach.

3. Methodology

3.1 Research Flowchart

The research methodology outlined in this study adhered to a systematic approach, as illustrated in the flowchart presented in Appendix A. The methodology commenced with the formulation of the research design, followed by an extensive review of relevant experimental work. Subsequently, the methodology was divided into two distinct components: the development of a numerical model and the application of qualitative methods. The final stages of the process encompassed data collection and rigorous data analysis to derive conclusive findings.

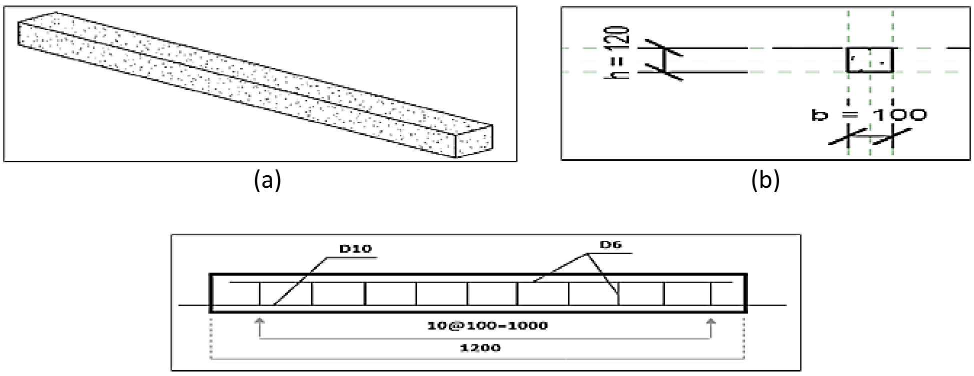
3.2 Research Design

This research adopted a mixed-method approach, integrating both a numerical model developed using the Finite Element Method (FEM) and a qualitative method. The Finite Element Method, implemented through MARC Mentat software, was utilized to construct a numerical model aimed at validating experimental results. FEM is a numerical technique that replaces structures with a finite number of elements connected at nodal points, allowing for the solution of a wide range of engineering problems. This method has significantly advanced the ability to address complex practical challenges [28]. The use of FEM tools provided a robust platform for investigating structural health monitoring and generating reliable outcomes.

Furthermore, to explore the potential of developing a numerical model for structural health monitoring, this research employed a qualitative method involving interviews with six engineers and two project managers. The qualitative research approach is characterized by an emphasis on understanding the significance individuals attribute to their experiences and observing people in their natural contexts [29].

3.3 Experimental Work

The experiment conducted in this study focused on the degradation process caused by mechanical and chemical attacks in the damage process of reinforced concrete (RC) beams [6]. The dimensions of the solid beam used in this experiment are depicted in Figure 2. To create the damaged RC beam with corroded reinforcement, an electrolytic process was employed to induce corrosion at several levels. Subsequently, a static loading test was conducted to determine the beam's ultimate strength. The assessment of damage caused by continuum mechanics considered both chemical and mechanical impacts. Three corrosion levels were established and quantified after the loading test using the electrolytic corrosion procedure. Specifically, one model had 0% corrosion, while two other models had corrosion levels measured at 6.13% and 11.71%. The results indicated that the beam with no corrosion exhibited a maximum strength of 25.72 kN, whereas the damaged beams with 6.13% and 11.71% degrees of corrosion reached strengths of 22.11 kN and 22.6 kN, respectively.

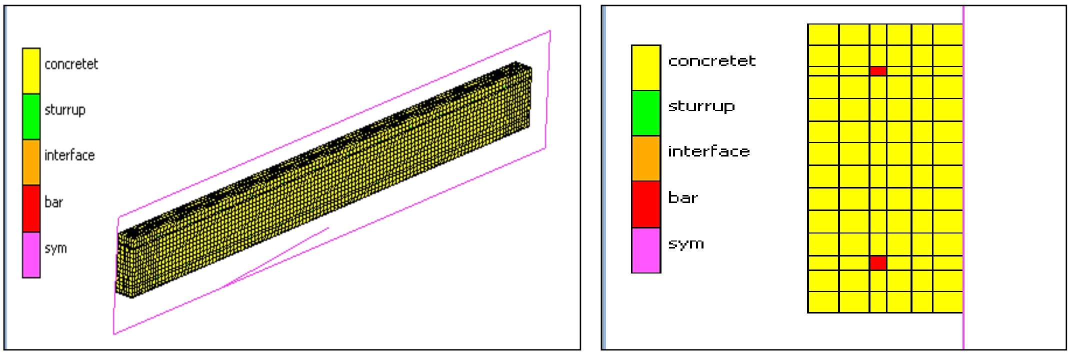


(a) (b) (c)

Fig. 2. Beam details (a) RC beam (b) Dimension (c) Rebar arrangement [6]

3.4 Beam Structure and Numerical Model Specification

To achieve objective one, a three-dimensional finite element model was developed using MARC Mentat 2018 software to simulate a reinforced concrete beam with 0% corrosion level. The software is capable of modeling various material types, including concrete and steel, making it suitable for this study. The finite element method was chosen for its reliability in studying and validating the performance of reinforced concrete beams compared to experimental work. Material properties of concrete and reinforcement were defined to input into the software for beam modeling. The detailed specifications of the numerical model are presented in Figure 3. The beam model was created using eight-node solid elements for 3D modeling. The concrete beam and reinforcement bars were modeled as solid elements, while shear reinforcement bars were represented using axial truss elements. These elements can simulate cracking in tension and crushing in compression. The numerical analysis focused on a flexural test scenario.



(a) (b)

Fig. 3. Cross-sectional beam element (a) Beam model (b) Material properties

3.5 Qualitative Method

To achieve the second objective, a qualitative method was employed, involving interviews with six Engineers and two Project Managers to explore the potential of developing a numerical model for structural health monitoring. The data collection process included individual interviews, telephone interviews, and online interviews. Interviews were scheduled during the respondents' working hours, from 9 am to 4 pm. Each interview lasted between 30 to 40 minutes, depending on the respondents' responses. The target population for the interviews was Engineers and Project Managers involved in structural inspection in Kuala Lumpur. According to the Board of Engineers Malaysia (BEM), there were a total of 110 registered Structural Engineers handling projects in Kuala Lumpur. The information gathered from these interviews will be compiled and analyzed to provide a comprehensive understanding of the respondents' perspectives.

3.6 Data Analysis

Data analysis involves collecting and analyzing data to summarize the results and support decision-making. In this study, data collected from the finite element method used to develop the numerical RC beam model was analyzed to validate and assess the accuracy of the model compared to experimental results. The accuracy of the numerical models was evaluated by comparing them with the experimental results, and the analysis results were presented in graphs, figures, charts, and tables to enhance clarity.

Additionally, data collected from the qualitative method, which involved conducting interviews, was analyzed using content analysis and represented in a matrix table. Content analysis is a method used to explore a dataset fully and determine underlying themes within the data. The data were thoroughly examined, and major themes were identified before being discussed in detail in the next section of the study.

4. Results

This chapter presents the results of the data analysis conducted for this research. The analysis includes data collected for the development of the numerical model using MARC Mentat software, which was validated against real experimental work. Additionally, the potential of the numerical model development for Structural Health Monitoring (SHM) was investigated using content analysis, and the findings are presented in the form of a matrix table based on the interview sessions. The analyzed data are presented in graphs and tables for clarity.

4.1 Numerical Model Development and the Validations of the Experimental Work

The analysis of the numerical model development focused on the flexural test and the measurement of ultimate strength. The results from the numerical analysis were compared with the experimental results. The numerical analysis was constructed based on geometric and material properties, which are detailed in Table 4 and are similar to the properties used in the laboratory experiments. The specific positioning of the numerical model is illustrated in Figure 4. Two concentrated load points were applied at a 200 mm movement section, fixed in all directions except for the x and y directions. The load was placed at the center span of the beam to measure displacement and load acting on the model. In this analysis, a load force of -10000N was applied to the beam model for the static loading test.

Table 4
Material properties

No	Material properties	Mass density	E	Ratio
1	Concrete	2.5e-09	-	-
2	Steel	7.85e-09	200,0000	0.3
3	Sturrup	7.85e-09	174,000	0.3

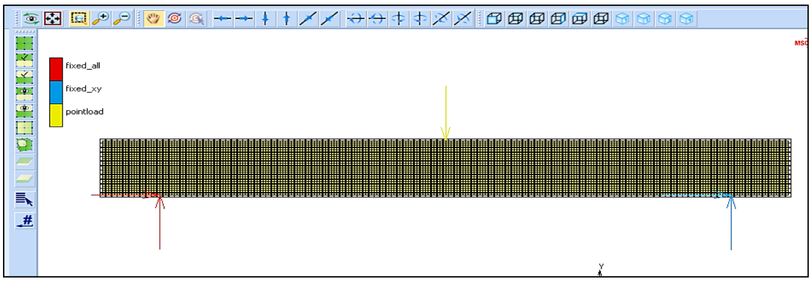
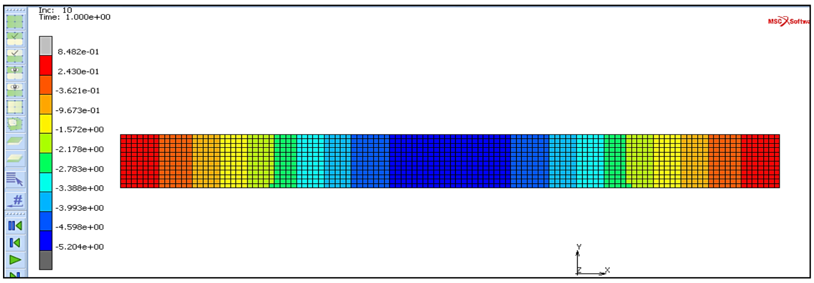
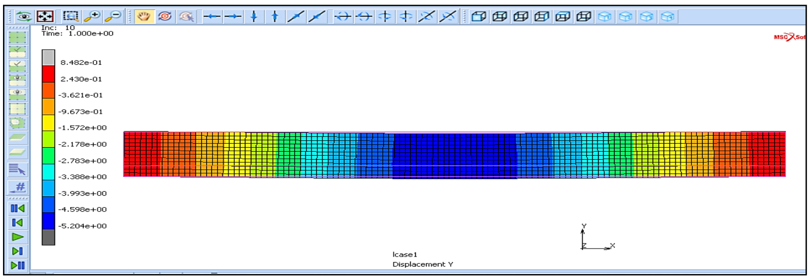


Fig. 4. Detail position of numerical model

Figure 5 presents the deflection of the beam model before and after the static loading test in the numerical analysis, while Figure 6 displays the beam from the experimental work after the static loading test. The results reveal minor bending at the center of the model due to the static loading test, indicating a state of failure. It is important to note that while the numerical model can predict the ultimate strength and demonstrate the deflection, the real experimental work allows for the observation of cracking, providing a more comprehensive understanding of the structure's behavior under load.



(a)



(b)

Fig. 5. Deflection of static loading test (a) before (b) after

Fig. 6. crack distribution after static loading test [6]

The relationship between ultimate strength and displacement in the beam model was analyzed, as shown in Figure 7. The analysis revealed a linear increase in strength and displacement up to the yield point, beyond which plastic deformation occurred. The peak point represented the maximum bending capacity, followed by structural failure. The numerical analysis-maintained strength steadily after the peak point, while the experimental results exhibited a gradual decrease as the structure failed. Flexural cracks appeared at 5kN in the experimental results, leading to a minor loss in stiffness. At the yield point (23kN for both numerical and experimental results), the first crack appeared, and the beam experienced a displacement of approximately 3-4 mm at mid-span for both sets of results. The maximum load observed was 25.72kN.

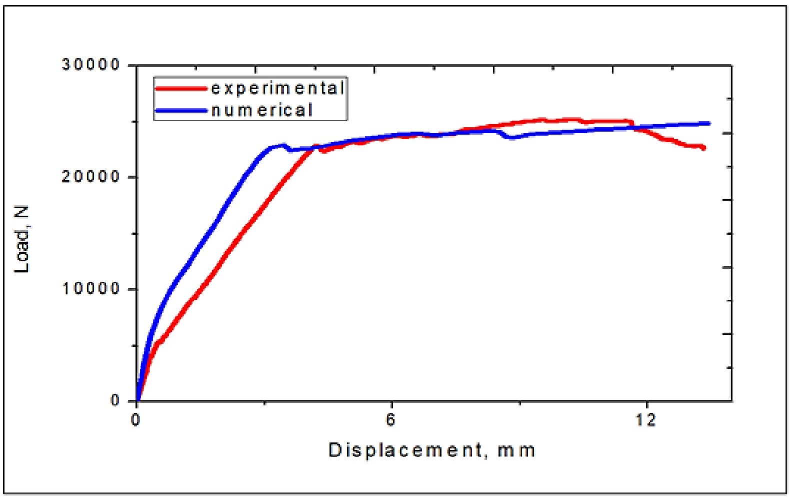


Fig. 7. Numerical/experimental validation for 0% of corrosion level

Comparing the numerical and experimental results, the numerical analysis indicated a higher beam strength than the experimental results. This is likely due to the lower probability of error or carelessness in numerical analysis compared to experiments. The alignment between the numerical and experimental results underscores the reliability and accuracy of the numerical model. This finding is consistent with previous research by Othman *et al.,* [26] which reported a maximum difference of 6.31% between laboratory experiments and ANSYS software predicted results for flexural strength, demonstrating high accuracy in structural analysis. This conclusion is further supported by the work of Yin *et al.,* [27] which also emphasized the accuracy of the finite element method in analyzing foamed concrete's flexural strength and deflection with minor deviation.

4.2 Potential of the Numerical Model Development in Structural Health Monitoring

The interview data were collected from eight participants, consisting of structural engineers and project managers based in Kuala Lumpur. The findings from these interviews are outlined below.

4.2.1 Respondent background

The respondents comprised engineers and project managers situated in Kuala Lumpur. Their positions, knowledge, and experience in building inspection qualify them as participants. Table 5 presents an overview of the respondents' backgrounds.

Table 5
Respondent's background

Respondents	Position	Experience
RI	Structural engineer	6 years
R2	Project manager	10 years
R3	Structural engineer	28 Years
R4	Engineer	15 Years
R5	Principle engineer	22 Years
R7	Resident engineer	22 years
R8	Project manager	8 years

4.2.2 Current practice of numerical model development for structural health monitoring

The current practices regarding numerical model development for structural health monitoring are summarized in Table 6, based on data obtained through interviews with selected respondents. The table outlines the benefits, challenges, risks associated with insufficient building structure inspection, and the potential of numerical model development for structural health monitoring.

i. Respondent's opinion on the benefits of numerical model development for structural health monitoring. Based on the interview session, the majority of respondents agreed that developing numerical analysis for structural health monitoring could lead to cost and time savings in inspections. Additionally, respondents R2 and R4 stated that developing a numerical model using software could reduce the need for manpower. "One of the benefits can be highlighted in terms of numerical model development for SHM is it can reduce the number of manpower in the phase of inspection as well as can reduce the entire of cost" (R4).
ii. Respondent's opinion towards the challenge of numerical model development for structural health monitoring.

Table 6
Current practice of numerical model development for structural health monitoring

Respondents	Benefits	Challenge	Can prevent inspection reduction
R1	Less cost and time	i. Lack of knowledge ii. Need a Certificate iii. High cost of training iv. High cost of software	Yes
R2	Less cost times Reduce manpower	i. Lack of knowledge ii. Accuracies	Yes
R3	Save cost and time	i. Accuracies ii. Lack of knowledge iii. Software updates	Yes
R4	Save cost and time Reduce manpower	i. Cost of software ii. Lack of knowledge iii. Specialist	Yes
R5	Initial steps of building care Can control building	i. Awareness of consumers ii. High cost for training	Yes
R6	Save cost and time	i. Accuracies	Moderate
R7	Save cost and time Faster decision making	i. Lack of knowledge ii. Need certificate from the government	Yes
R8	Good for references Save cost and time	i. Limitation old data ii. Limit the size of the building	Yes

Based on the responses, most of the respondents identified the lack of knowledge about software and the accuracy of data collection as key challenges. Respondents R1, R2, R3, and R7 emphasized that those responsible for inspections might lack the necessary knowledge for analyzing data using software. Additionally, respondents R2, R3, and R6 expressed concerns about data accuracy, noting that the data obtained might be insufficient for accurately assessing the structure's strength.

"The most challenging in development of the numerical model in structure health monitoring is lacking on the knowledge of using the software. This is because the software is always updated every year, which could change the system." (R7).

"One of the challenges that may occur is about the accuracies of the data result obtained. The data taken may not be complete enough to detect changes in the material and geometric properties for the structure" (R6).

i. Respondent's opinion on the possibility of preventing inspection reduction using this numerical model.All respondents agreed that the numerical model could help prevent reductions in inspections. "Yes, I agree with this, because, for a structure that has been finished and handed over to the client, or for an existing building, maintenance is no longer a priority and may not be performed an inspection at all" (R2).
ii. Respondent's opinion on the potential and suggestion for improvement in Numerical Model Development for Structural Health Monitoring.

Based on the current practices of developing numerical models for structural health monitoring, respondents provided additional suggestions regarding the potential applicability of this model in the industry. Their feedback and suggestions are summarized in Table 7.

Table 7
Potential and suggestions in numerical model development for structural health monitoring

Respondents	Potential	Suggestion/Improvement
R1	Moderate	Training among engineer
R2	Yes	On-site inspection also needs to conduct
R3	yes	Analysis on physical. Analysis included on all structure member
R4	Yes	Analysis of underground structure strength
R5	Moderate	Cooperate with facility management
R6	Yes	Training among engineers and consultants
R7	Yes	Training among engineer and consultant
R8	Yes	Alerting the client to keep the building data

Based on the research findings, all respondents concur that the development of numerical models for structural health monitoring holds significant potential for application in the construction industry. They acknowledge its numerous benefits, particularly in terms of cost efficiency. However, respondents also offer suggestions for enhancing this method for structural health monitoring. R1, R6, and R7 emphasize the need for industry incentives to encourage inspection personnel to undergo training on digital software, ensuring proficiency in software analysis. R2 and R3 suggest that while this method can be implemented, it should be complemented by on-site inspections for visual confirmation, meeting industry standards for accuracy and quality. Furthermore, R3 and R4 propose that the analysis could be enhanced by conducting individual analyses of each structural member, including underground structures, to improve the reliability of strength results. According to R5, reliability could be further enhanced by collaborating with facility management to monitor buildings based on acquired data. Lastly, R8 highlights the importance of alerting clients to the need to safeguard building data, ensuring that engineers can access it promptly when inspections are required.

5. Conclusions

In conclusion, this study introduces a modern technique for structural health monitoring, proposing a new approach using Marc Mentat software to develop and validate a numerical model against real experimental data. The results demonstrate that the numerical model developed in Marc Mentat can effectively validate experimental findings, as the analysis closely aligns with experimental results within an acceptable margin. This validation confirms the reliability and accuracy of the numerical model, indicating its potential for predicting structural behavior with good precision. The development of the numerical model not only enhances inspection performance but also proves cost-effective for maintenance.

Furthermore, the study explores the potential of numerical model development in structural health monitoring, with all respondents expressing agreement regarding its potential implementation. Suggestions for improvement to enhance the accuracy of data analysis were also noted. Future research will expand on these findings by developing models for additional existing structures and predicting their future strength.

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