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Original Article

A COMPREHENSIVE REVIEW OF FINITE ELEMENT MODELLING TECHNIQUES FOR REINFORCED CONCRETE BEAMS UNDER IMPACT AND BLAST LOADING CONDITIONS

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ABSTRACT

RC beams are important structural components that are becoming vulnerable to extreme dynamic loads like impact and blast events whereby they experience complex nonlinear responses where strain rates are high, energy transfer is rapid and localized damage. It is vital to understand how they behave under these conditions in order to achieve structural safety and resilience. The Finite Element Modelling (FEM) has proved to be a strong computational model that can effectively model material nonlinearity, stress wave propagation, cracking and failure mechanisms that cannot be effectively modeled by experimental techniques. This paper is a review of FEM methods used in the study of RC beam under impact and blast loading, with the main issues addressed in the paper being modelling methods, constitutive models of materials, methods of loading, and failure, and validation strategies. It also looks at recent developments, such as hybrid modelling methods, incorporation of high-performance materials, and also explains the current problems, such as the computational complexity and uncertainty in the parameter. The purpose of the review is to offer a synthesized view of the existing practices, and to determine the future research directions towards improving the face validity and efficacy of numerical simulations in structural engineering.

Keywords: Finite Element Modelling (FEM), Reinforced Concrete Beams, Impact Loading, Blast Loading, Dynamic Analysis, Concrete Damage Plasticity (CDP)

INTRODUCTION

One of the most critical structural elements used in most buildings, bridges, and other infrastructure systems is reinforced concrete (RC) beam because it is strong, durable, and economical. Nevertheless, over the past years, the rising frequency of extreme events including vehicular impacts, accidental explosions, and intentional blast attacks have become a serious issue with regard to the safety and performance of RC structures Li et al. (2016). The dynamic loads caused by these events are fundamentally different to traditional static loads and present a severe challenge to structural design and analysis.

Impact and blast loads are high in intensity, have short duration and rapid transfer of energy leading to complex structural responses Solahuddin and Yahaya (2023). In this case, high strain-rate effects, stress wave propagation and nonlinear material behavior occur in RC beams resulting in damage mechanisms like cracking, scabbing, spalling and potential structural failure Naser et al. (2021). Although experimental research has yielded useful information in understanding these behaviors, they are usually constrained by their high cost, time, and practical constraints associated with imitating real world extreme loading conditions.

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Transparency: The authors affirm that this manuscript presents an honest, accurate, and transparent account of the study. All essential aspects have been included, and any deviations from the original study plan have been clearly explained. The writing process strictly adhered to established ethical standards.

Finite element modelling (FEM) has become an effective and dependable tool of computation in this regard, in the study of the behaviour of RC beams under dynamic loads. FEM can be used to simulate the stress distribution, patterns of deformation, cracks propagation, and mechanisms of failure in detail, which is challenging to observe in experiments Saleem et al. (2025). This paper attempts to present a broad overview of the modelling techniques of RC beam under impact and blast loading, the modelling strategies, behaviour of materials, representation of loading and the challenges associated with the modelling, as well as future research direction in this area.

OBJECTIVES OF THE REVIEW

- To critically review and analyze FEM techniques used for RC beams under impact and blast loading conditions.
- To examine various material models, loading representations, and failure mechanisms influencing the dynamic response of RC beams.

BEHAVIOUR OF RC BEAMS UNDER IMPACT AND BLAST LOADING

Impact and blast borne reinforced concrete (RC) beams have complex structural behaviour attributed to high strain rates, stress-wave propagation and nonlinear material response Nawar et al. (2024). These dynamic conditions, unlike those of a static loading, lead to a rapid transfer of energy and localized damage, which has a great impact on structural performance and failure modes.

BEHAVIOUR UNDER IMPACT LOADING

Impact loading the loading that results due to the impact of a moving object on an RC beam to produce short term, but intense, contact loads. This results in localized damages as surface cracking, crushing, impact craters and radial crack propagation. All the stress waves or forces at the point of contact are distributed throughout the beam leading to flexural deformation and shear stresses. The factors which affect the response are impact velocity, mass, reinforcement ratio and boundary conditions Temsah et al. (2018). Higher velocity and mass contribute to the magnitude of the damage and a reinforcement adequately will improve the energy absorption and decrease the crack propagation. Both experimental and numerical results had been reported with similar dynamic reactions including stress wave effects.

BEHAVIOUR UNDER BLAST LOADING

The pressure wave, caused by explosions, on the surface of the structure is known as blast loading. A typical blast is a positive phase which has an accelerated increase in pressure and a decay and a negative phase which brings suction effects. The conditions bring about serious damages like the scabbing of the rear surface, spalling of the front surface and flexural or shear failure. The amount of damage is dependent on charge weight, stand-off distance, and material properties. Review shows that an increase in explosive intensity and a decrease in the stand-off distance have a great impact on structural damages Ibrahim et al. (2017). More sophisticated types of modelling have also been conducted that have helped to determine the areas of the damage that are most critical in the case of a blast.

COMPARATIVE DISCUSSION OF IMPACT AND BLAST LOADING

Impact and blast loads vary in nature and impacts. Impact loading and the direct contact forces cause the damage to be very localized, whereas the pressure waves in the blast loading causes it to be localized and distributed. Mechanical parameters that control impact behavior are velocity and mass, whereas the blast effect relies on explosive properties like charge weight and stand-off distance. In addition, internal damage such as scabbing will also occur due to blast loading stress waves. The important observations of the prior experiments of the behavior of RC beam under dynamic loading are summarized in Table 1.

Table 1

Table 1 Key References on Behaviour of RC Beams under Impact and Blast Loading

Author(s) & Year	Study Focus	Key Findings	Relevance to Section
Senthil et al. (2020)	Review of RC structures under blast loading	Identified spalling, scabbing, and major failure mechanisms	Supports blast damage discussion
Thiagarajan et al. (2015)	Experimental and FEM study of RC slabs	Highlighted stress wave propagation and validation of FEM	Supports dynamic response explanation
Kolbadi et al. (2017)	Nonlinear dynamic analysis under explosion	Showed nonlinear structural behavior under blast loads	Supports nonlinear behavior discussion

Chen et al. (2015)	Numerical analysis of RC beams	Identified flexural and shear failures under blast loading	Supports failure mechanisms
Anas et al. (2022)	CEL-based FEM blast modelling	Identified critical damage zones and blast effects	Supports advanced modelling discussion

FINITE ELEMENT MODELLING APPROACHES

Finite Element Modelling (FEM) offers a robust numerical method in order to simulate the complicated nature of reinforcement concrete (RC) beams under dynamic loads like impact and blast. These conditions include big deformations, nonlinear material behaviour and high strain-rate impacts, and where advanced modelling tactics are necessary. As shown in Figure 1, various FEM methods are segregated according to the nature of the interaction between the computational mesh and material under deformation.

Figure 1

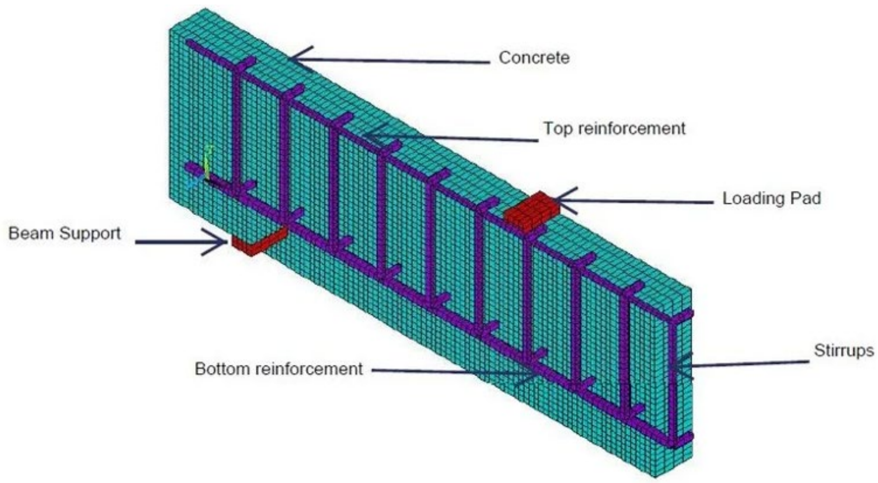

Figure 1 Finite Element Modelling Approaches for RC Beams Ibrahim and Nabil (2019)

1) Lagrangian Method

Lagrangian has been extensively applied to structural analysis, in which the mesh moves with the material. This allows precise monitoring of stress, strain and propagation of cracks, and is adapted to impact and structural deformation studies. But it has a weakness in that it distorts the mesh during large deformations, which can decrease accuracy.

2) Eulerian Method

The Eulerian method operates on a fixed mesh where material is flowing so that it can be used in the blast waves and fluids-structures interaction Talaat et al. (2022). Although it does not distort the mesh, it does not have the ability to capture finer structural behavior, like cracking.

3) Coupled Eulerian–Lagrangian (CEL) Method

The CEL approach is a combination of the two, in which the structure is modelled in a Lagrangian framework, and the surrounding medium in a Eulerian framework. This allows the interaction of the blast wave with structures to be accurately simulated, at the cost of high-level computation.

4) Smooth Particle Hydrodynamics (SPH)

SPH is a mesh free technique whereby material is represented as particles and is therefore applicable in simulating large deformations and fragmentation. It gets rid of mesh distortion problems, but can be less accurate in stress and more expensive to compute Qu et al. (2016).

5) Element Types and Reinforcement Modelling

In FEM simulations, concrete is usually modeled as a solid element (three dimensional) and reinforcement is modeled as beam or truss elements. They are usually combined in the embedded element technique, which provides compatibility of deformation without directly modelling bond interaction.

MATERIAL MODELLING OF CONCRETE AND STEEL

Proper material modelling is an important aspect of finite element analysis, because the effectiveness of the numerical prediction depends heavily upon the ability of the model to capture nonlinear and strain-rate-dependent behaviour of materials. Impact and blast loads on reinforced concrete beams have complex responses involving cracking, crushing, yielding, and degrading the stiffness and should be realistically represented in the model.

Both concrete and steel as shown in Figure 2 exhibit some unique nonlinear stress strain behavior that controls their behavior in extreme loading situations.

Figure 2

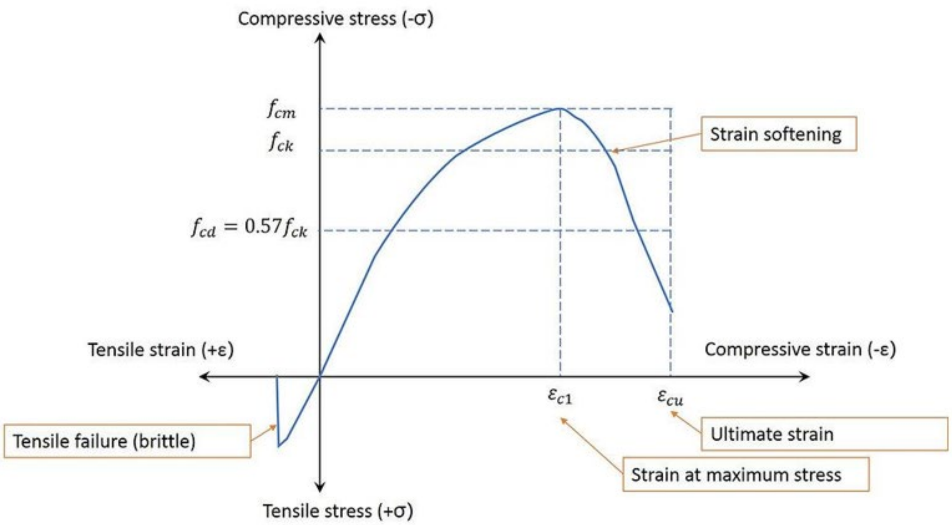

Figure 2 Constitutive Behaviour of Concrete and Steel under Dynamic Loading Del Linz et al. (2016)

Concrete is a quasi-brittle material and thus it does not act in the same way when subjected to tension and compression and as such, it is a very difficult material to model. The Concrete Damage Plasticity (CDP) model is one of the constitutive models that is commonly used because of its capability to simulate tensile cracking, compressive crushing and degradation of stiffness in static and dynamic conditions. As shown in Figure 2, the CDP model is effective in the representation of the evolution of the damage and applicable in general reinforced concrete analysis.

To capture more sophisticated high strain-rate conditions like blast and impact loading, the Johnson Holmquist Concrete (JHC) model is more sophisticated, as it includes strain-rate sensitivity, pressure dependency, and progressive damage Gouda et al. (2023). On the same note, other models like the Karagozian and Case (K&C) and Win Frith models provide a better capability of simulating complex failure mechanisms especially in explosive environments.

In contrast to concrete, steel reinforcement has ductile behavior and is normally represented by elastic-plastic formulations with strain hardening. More complicated models like the Johnson Cook model are used under high strain-rate conditions to explain strain-rate effects and thermal softening. As can be seen in Figure 2, plastic deformation potential of steel is essential in improving energy absorption capacity of RC beams.

Concrete and steel reinforcement interaction is the other critical factor of material modelling. Even though the assumption that the bond between the elements is perfect is made in many finite element models, in reality, this might not be the case with real structural behavior. Bond-slip interactions affect the load transfer, crack formation and general structural behaviour. However, due to its complexity and lack of standardized parameters, bond-slip modelling remains one of the major challenges in FEM.

MODELLING OF IMPACT AND BLAST LOADS

Proper modeling of loading conditions is critical in finite element modeling because it has a direct impact on the structural response predicted. Impact and blast loads vary greatly in terms of physical nature and hence cannot be modelled in the same way. Although contact interaction is used to represent impact loads, the blast loads are modeled by the pressure-time histories mimicking the effects of explosives Abd-El-Nabi et al. (2023).

Impact loading is typified by a sharp increase in contact force whereas, as shown in Figure 3, blast loading follows a pressure-time curve with a sharp peak and decaying exponentially.

Figure 3

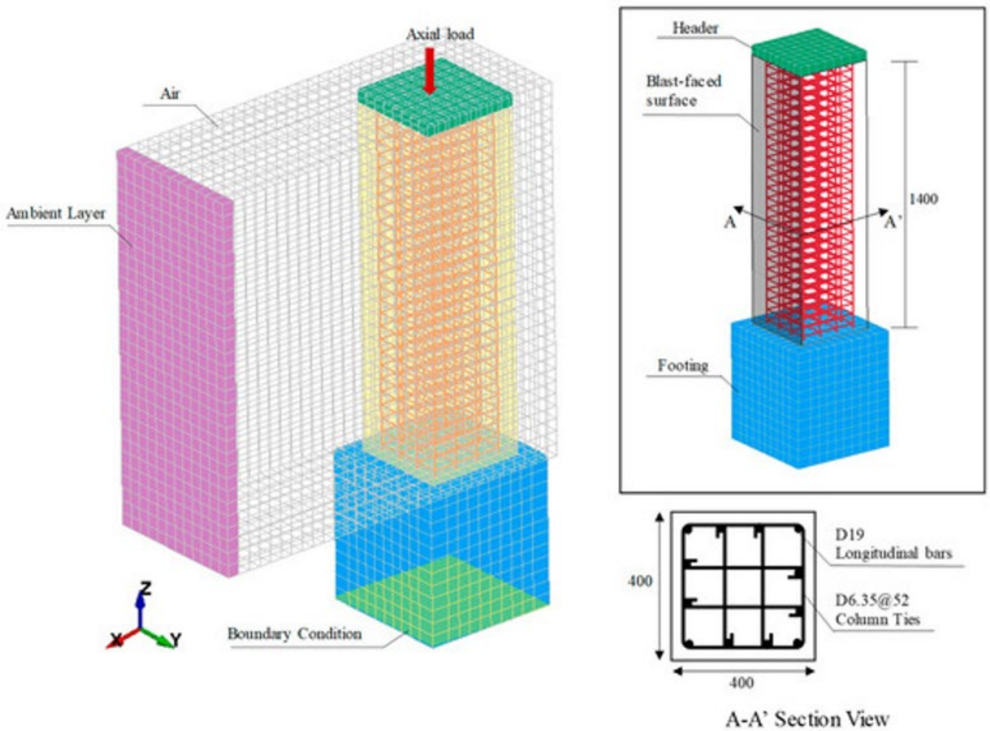

Figure 3 Representation of Impact and Blast Load Functions in FEM Zhang et al. (2019)

Contact algorithms are typically used to model impact loads and are used to simulate interaction between the impacting body and the RC beam. In a lot of researches, drop-weight simulations are conducted, in which an identified mass can be permitted to hit the structure at a certain speed. The force-time response is the result of the velocity of impact, the mass of the impacting object and the stiffness of the contact. These parameters control the energy transfer process and the degree of structural damage.

Conversely, the blast loads are modeled by analytical or empirical models that specify the pressure change with time Alshaarbaf et al. (2023). The Friedlander equation, representing the rapid increase and exponential decrease of the blast pressure, is one of the most common representations that was shown in Figure 3. The other popular method is the TNT equivalent method in which the explosive charge is in terms of an equivalent mass of TNT to make the analysis easier.

Also, blast loads are widely simulated using the CONWEP (Conventional Weapons Effects Program) model, which is also widely available in finite element software. It offers empirical relationships based on charge weight and stand-off distance to determine parameters like peak overpressure and impulse. All these models allow simulating the effect of a blast wave propagation and its interaction with structural elements.

Table 2 summarizes the important features of impact and blast load modelling methods.

Table 2

Table 2 Load Modelling Techniques in FEM Kadhim et al. (2020)

Load Type	Method Used	Key Parameters	Application
Impact	Contact / Drop-weight	Velocity, mass, stiffness	Structural impact analysis
Blast	TNT / Friedlander / CONWEP	Pressure, impulse, duration	Explosion simulation

As shown in Table 2, the impact loading is mostly controlled by mechanical parameters, and the blast loading is controlled by the explosive features and the behavior of waves propagation. These loads should be accurately modelled to reflect the real structural behaviour and determine the failure mechanisms of RC beams.

FAILURE MECHANISMS AND MODEL VALIDATION

A complex interplay of nonlinearity of the material, stress wave propagation, and high strain rates determines the structural response of reinforced concrete (RC) beam under impact and blast loading. The identification and analysis of these failures' modes have been undertaken with a lot of accuracy using finite element simulations Alañón et al. (2018).

The combination of flexural, shear and localized surface damage is common in RC beams under dynamic loading conditions as shown in Figure 4.

Figure 4

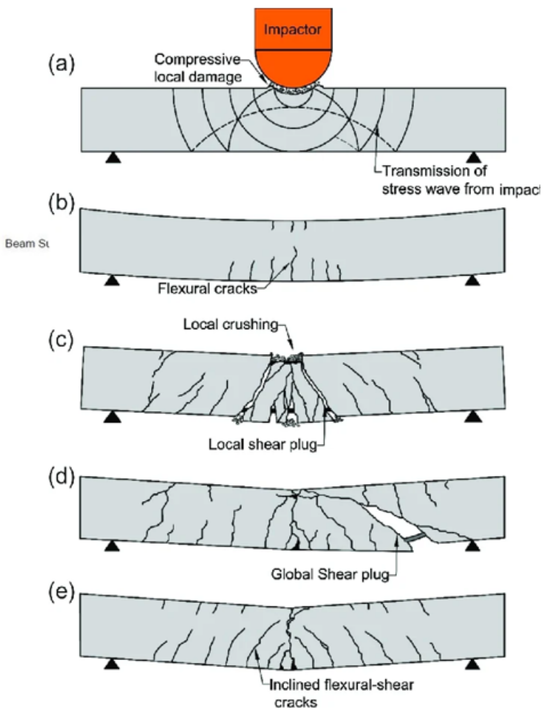

Figure 4 Failure Mechanisms in RC Beams under Impact and Blast Loading Islam et al. (2025)

The main cause of flexural failure is when the bending moments are excessive and therefore, the beam develops vertical cracks in the tension zone. At increased loading rates shear failure can prevail, with diagonal cracking, and abrupt brittle behaviour. Along with these global failure modes, localized damage phenomena like spalling and scabbing can be of special concern during blast loading Kim et al. (2023). Spalling is used to describe the expulsion of the concrete material on the front side, caused by high compressive stresses, and scabbing on the back side caused by tensile stress waves reflected in the beam as shown in Figure 4.

Failure mechanisms are also important with respect to reinforcement behavior. During the moderate loading conditions, steel bars might yield, which helps in providing ductility and energy absorption. But at high impact or blast loads, reinforcement rupture can take place and cause disastrous structural collapse.

All the failure modes experienced by RC beams when subjected to dynamic loading are listed in Table 3, indicating their nature and the causes behind them.

Table 3

Table 3 Failure Modes in RC Beams under Dynamic Loading Wu et al. (2020)

Failure Mode	Description	Primary Cause
Flexural	Vertical cracking in tension zone	Bending stresses
Shear	Diagonal cracking	Shear forces
Spalling	Front surface concrete loss	High compressive stress
Scabbing	Rear surface concrete detachment	Reflected tensile waves

Reinforcement Failure	Yielding or rupture of steel	Excessive stress and strain

Finite element model validation is an essential procedure to make sure that numerical simulations are reliable. The validation of the model is usually undertaken by comparing the results of the simulations with the experimental observations, which include the load-deflection behavior, crack pattern and failure mode. Predictive capability is greatly improved as demonstrated by the correlation between simulated and experimental results as the material properties, boundary conditions and loading parameters are accurately modelled. Thus, not only does validation enhance confidence in FEM results, but it also guarantees their applicability in real-life structural design and safety analysis.

ADVANCES, CHALLENGES, AND FUTURE DIRECTIONS

Finite element modelling of impact and blast loading of reinforced concrete (RC) beams has achieved big improvements in recent years. The main trends in these developments have been to enhance the accuracy, efficiency, and applicability of numerical simulations of complex dynamic behavior Sadique et al. (2022).

One of the key advancements is the incorporation of high-performance materials such as ultra-high-performance concrete (UHPC) and fiber-reinforced concrete. These materials are stronger, ductile and withstand extreme loading conditions, making them to have better overall structural performance in the cases of impact and blast Yao et al. (2016). This has been made possible by their incorporation into finite element models and has made it possible to predict damage and failure mechanisms more realistically.

The other significant innovation is the introduction of hybrid modelling, especially the integration of the conventional finite element methods with mesh-free methods like Smooth Particle Hydrodynamics (SPH) Mortar et al. (2022). The combination of these enables them to simulate more effectively large deformations, material fragmentation, and extreme conditions of damage that are hard to model with traditional methods.

Moreover, artificial intelligence and machine learning in combination with finite element modelling have become an exciting research field. By these methods, it is easier to formulate surrogate models that can dramatically save the computation time without losing feasible accuracy. This has led to complex simulations, which were once demanding of computational resources, being done in a more efficient manner.

Irrespective of these developments, there are still a number of challenges that remain to inhibit the dynamic loading of RC beams in the analysis using FEM Gholipour et al. (2019). Among the key concerns, the absence of standardized material parameters, especially at high strain-rate conditions, is likely to cause inconsistent results of the simulations. Moreover, the modelling of the bond-slip interaction between the concrete and the steel reinforcement is a complicated issue because it is a nonlinear and interface-dependent phenomenon.

The other major problem is that the computational cost of detailed three-dimensional simulations is very high, particularly when simulating blast loads and large-scale structural systems. Also, experimental data that can be used to validate is scarce, and thus, it becomes difficult to effectively verify and calibrate numerical models.

The future review must consequently be directed towards the establishment of coherent and standardized material models that could be consistently used in various loading conditions. Strengthening multi-hazard analysis capacity also needs to be developed, which allows the simulation of combined loading conditions like blast, impact, and seismic conditions. Moreover, the ongoing implementation of the artificial intelligence and FEM is likely to result in an increase in the computational efficiency and predictive accuracy Lin et al. (2023) , which resulted in the more accessible and viable simulation to be applied in the practice of engineering.

CONCLUSION

The study concludes that Finite Element Modelling (FEM) has already become an invaluable component in the comprehension and forecasting of the complicated behaviour of reinforced concrete (RC) beams under impact and blast loading circumstances. This survey indicates that the combination of advanced modelling schemes such as Lagrangian, Eulerian, CEL and SPH techniques with high quality material models such as CDP and JHC can be used to simulate accurately nonlinear responses, stress wave propagation and failure mechanisms. The review also highlights the significance of proper load representation, and model validation in delivering credible numerical results. Although much has been achieved, there are still issues like high cost of computation, the absence of standardized material parameters and the inability to model bond-slip interactions. Consequently, future studies need to aim at the development of coherent constitutive models, enhancing the capability to perform multi-hazard analysis, and incorporating the new technologies like artificial intelligence to increase the accuracy and efficiency. In general, it can be concluded that FEM remains crucial in the development of design and safety evaluation of RC structures in the context of the extreme dynamic loading.

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