A review on Fracture Propagation in Concrete: Fundamentals, Experimental Techniques, Modelling and Applications

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Abstract:

This paper provides a comprehensive overview of fracture propagation in concrete, covering various aspects ranging from fundamentals to applications and future directions. The introduction section presents an overview of fracture propagation in concrete, emphasising its importance in understanding the behaviour of concrete structures. The fundamentals of fracture propagation are explored, including concrete as a composite material, crack initiation and propagation mechanisms, types of fractures and factors influencing fracture propagation. Experimental techniques for studying fracture propagation are discussed, encompassing both non-destructive and destructive testing methods, such as acoustic emission, ultrasonic testing, digital image correlation and advanced imaging techniques like X-ray tomography and scanning electron microscopy. Modelling approaches, including continuum damage mechanics, finite element method, discrete element method, lattice discrete particle model and hybrid modelling approaches, are reviewed for simulating and predicting fracture propagation behaviour. The applications of fracture propagation in concrete are highlighted, including structural health monitoring, design optimisation, failure analysis and repair and rehabilitation strategies. The research opportunities for further improvement are addressed. The paper serves as a valuable resource for researchers, engineers and professionals in the field, providing a comprehensive understanding of fracture propagation in concrete and guiding future research endeavours.

Keywords: Fracture propagation, crack initiation, X-ray tomography, discrete element method, continuum damage mechanics.

1. Introduction

Fracture propagation in concrete is a complex and critical phenomenon that plays a significant role in the behaviour and performance of concrete structures. Understanding how cracks initiate, propagate and interact in concrete is essential for ensuring the safety, durability and functionality of these structures. Concrete, as a composite material, exhibits unique fracture characteristics due to its heterogeneous nature (Ortiz and Popov, 1982; Konsta-Gdoutos et al. 2010; Bencardino et al. 2010; Jones, 2018). Fracture propagation in concrete can occur through various mechanisms, including microcracking, crack bridging, aggregate interlock and matrix failure (Santiago and Hilsdorf, 1973; Shah et al. 1995; Li and Maalej, 1996; Rossi et al. 2014; Sarfarazi and Haeri, 2016). These mechanisms are influenced by factors such as material properties, loading conditions, environmental effects and the presence of reinforcement.

The types of fractures encountered in concrete can vary from tensile cracks to shear cracks and can occur in different locations, such as near the surface, within the bulk material, or at the interface between different materials (Ohno and Ohtsu, 2010; Aldahdooh and Bunnori, 2013; Nor et al. 2013; Ohno et al. 2014). Understanding the behaviour of these fractures is crucial for assessing the structural integrity and predicting the performance of concrete elements. Researchers have developed various experimental techniques to study fracture propagation in concrete. Non-destructive testing methods, such as acoustic emission, ultrasonic testing, and digital image correlation, allow for real-time monitoring and detection of cracks in concrete structures (Aggelis, 2011; Dumoulin et al. 2015; Dong et al. 2017; Nejati et al. 2020; Saleem and Gutierrez, 2021; Mukhtar and El-Tohfa, 2023). Destructive testing methods, including three-point bending, compact tension and Brazilian tests, provide valuable data on fracture toughness and crack growth (Ozbolt et al. 2011; Ozbolt et al. 2013; Huang et al. 2018; Yin et al. 2020; Padilla et al. 2022). In addition to experimental techniques, computational modelling approaches have been developed to simulate and predict fracture propagation in concrete. Continuum damage mechanics, finite element method, discrete element method and lattice discrete particle model are some of the modelling techniques used to capture the behaviour of cracks and their interactions with the surrounding material (Alfaiate et al. 1997; Sancho et al. 2007; Ooi and Yang, 2011; Cusatis et al. 2011; Meza-Lopez et al. 2020; Xie et al. 2020; Jin et al. 2021; Park et al. 2022).

The knowledge of fracture propagation in concrete finds applications in various fields. Structural health monitoring techniques utilise the understanding of crack propagation to assess the condition and integrity of concrete structures, allowing for early detection of potential failures. Design optimisation of concrete structures takes into account fracture propagation behaviour to enhance their performance and resistance to cracking. Failure analysis and risk assessment involve studying fracture propagation to identify the causes of structural failures and mitigate potential risks. Repair and rehabilitation strategies consider the behaviour of cracks to develop effective methods for repairing and strengthening damaged concrete structures.

While significant progress has been made in the study of fracture propagation in concrete, there are still challenges and areas for improvement. Further research is needed to explore the microstructural effects on fracture behaviour, investigate dynamic fracture propagation under dynamic loading conditions and develop sustainable and eco-friendly concrete solutions with enhanced fracture resistance. Advanced sensing and monitoring techniques, integration of artificial intelligence and machine learning and field studies on real-world structures experiencing fracture propagation are among the research opportunities that can contribute to advancing the understanding of this important phenomenon.

The motivation behind this review paper is to address the critical need for a comprehensive and up-to-date synthesis of knowledge in this field. By providing a consolidated overview of the fundamentals, experimental techniques, modelling approaches, applications, challenges and future directions, the review paper aims to fill the existing gaps and stimulate further research. It seeks to motivate researchers, engineers and professionals by emphasising the importance of understanding fracture propagation in concrete for ensuring structural safety, durability and performance. Ultimately, the review paper aims to contribute to the advancement of knowledge and the development of innovative strategies in the field of fracture propagation in concrete.

The scope of this paper encompasses a wide range of topics related to the phenomenon. It covers the fundamentals of fracture propagation, experimental techniques for studying fractures, modelling approaches, applications in structural engineering and future research opportunities. However, it is important to note the limitations of the paper, including the possibility of not capturing every single research study in the field due to the vastness of the topic. Additionally, the paper does not delve deeply into specific subtopics or emerging research areas. The scope and limitations should be considered when interpreting the findings and applying them to specific contexts.

2. Fundamentals of Fracture Propagation in Concrete

2.1 Concrete as a Composite Material

Concrete is commonly referred to as a composite material due to its composition and structural characteristics. As a composite material, it exhibits a combination of properties that arise from the interaction between its components, namely the matrix, aggregates and additives. This composite nature of concrete plays a significant role in its overall performance and has implications for its design, construction and durability. One key aspect of concrete as a composite material is the matrix, which consists of cement, water and additives. Cement acts as a binder, providing cohesion to the mix and enabling it to harden into a solid mass. The hydration process of cement, where water reacts with cement particles, forms a matrix that binds the aggregates together and transfers loads within the material. The properties of the matrix, such as its strength, durability and resistance to chemical attack, greatly influence the performance of the concrete (Aıtcin, 2003; Li et al. 2020; Tayeh et al. 2022).

The aggregates in concrete contribute to its mechanical properties, such as strength, stiffness and density (Ke et al. 2009; Cachim, 2009). They can be coarse aggregates (e.g., gravel or crushed stone) and fine aggregates (e.g., sand), which provide bulk to the material and fill the voids in the matrix. The size, shape and distribution of aggregates impact the workability, strength and durability of the concrete (Basheer et al. 2005; Medina et al. 2014; Aissoun et al. 2016; Sokhansefat et al. 2019). Additionally, aggregates can influence other properties like thermal conductivity and shrinkage (Kim et al. 2003; Demirboga and Kan, 2012). The composite nature of concrete allows for the optimisation of specific characteristics by incorporating additives or admixtures. These substances are introduced during the mixing process to enhance workability, modify setting time, improve durability, or impart special properties like increased water resistance or improved chemical resistance. Admixtures can also address specific challenges, such as controlling air content or reducing the potential for cracking. The interaction between the matrix and aggregates in concrete is crucial for its overall performance. The matrix binds the aggregates together, provides protection against environmental factors, and helps distribute the applied loads. By transferring stresses to the aggregates, the matrix enhances the strength and load-bearing capacity of the concrete. The selection and proportioning of materials can be tailored to optimise the desired properties of the composite.

Understanding concrete as a composite material has significant implications for its design and construction. Engineers and researchers can study the behaviour of its components to develop advanced mix designs, optimise the strength-to-weight ratio, improve durability and explore sustainable alternatives. This knowledge also enables the development of innovative construction techniques, such as fibre reinforcement or self-healing concrete, which enhance the material's performance and extend its service life. However, concrete as a composite material also poses challenges and limitations. Its inherent brittleness and susceptibility to cracking, especially under tensile loads, require additional measures to enhance its performance. Reinforcing materials, such as steel bars or fibres, are often incorporated to increase tensile strength and control crack propagation (Olesen, 2001; Yang et al. 2012; Ghalehnovi et al. 2019). The long-term durability of concrete can be affected by factors like chemical attack, freeze-thaw cycles and moisture ingress, necessitating proper design, maintenance and repair strategies.

2.2 Crack Initiation and Propagation Mechanisms

Crack initiation and propagation in concrete are influenced by various factors such as tensile stresses, chemical reactions, corrosion, stress concentrations, aggregate interlock, fracture toughness, microcracking and environmental effects. Tensile stresses exceeding the concrete's strength lead to crack initiation, while stress concentrations and weakened interfaces facilitate crack propagation. Understanding these mechanisms helps in developing strategies for crack prevention and control, including improved mix designs, reinforcement with fibres, and monitoring techniques. Addressing crack initiation and propagation is crucial for ensuring the durability and longevity of concrete structures, enhancing their performance and safety.

2.2.1 Crack Initiation Mechanisms

Tensile stresses in concrete can arise from various sources, and when they exceed the tensile strength of the material, cracks can initiate (Chen and Yuan, 1980; Erzar and Forquin, 2010). External loads, such as applied forces or structural loads, can create tensile stresses that exceed the concrete's capacity to resist. Temperature differentials within the structure can also induce differential expansion and contraction, leading to tensile stresses and crack formation (Emorg and Bernander, 1994; Whittier et al., 2004; Maruyama and Lura, 2019). Additionally, restrained volume changes, such as those caused by drying shrinkage or thermal expansion, can generate tensile stresses in the concrete.

Chemical reactions can also contribute to crack initiation in concrete. Alkali-aggregate reaction (AAR) occurs when reactive minerals in the aggregates react with alkalis from the cement paste, resulting in the formation of expansive reaction products (Glasser, 1991; Peng et al., 2020). The expansion exerted by these reaction products leads to microcracking and the initiation of cracks. Similarly, sulphate attack involves the reaction between sulphates from external sources, such as groundwater and the cement paste (Lawrence, 1990; Roziere et al. 2009). This reaction results in the formation of expansive compounds that cause cracking in the concrete.

Corrosion of steel reinforcement is another significant factor influencing crack propagation in concrete. When steel reinforcement is exposed to moisture and oxygen, it can undergo corrosion (Zhang et al. 2009; Al-Harthy et al. 2011; Shaikh, 2018). The formation of rust on the steel surface increases its volume, generating expansive forces that exert tensile stresses on the surrounding concrete. Over time, these tensile stresses can initiate cracks and compromise the structural integrity of the concrete.

2.2.2 Crack Propagation Mechanisms

Stress Concentration: Once a crack initiates, stress concentrations occur at the crack tip due to the abrupt change in geometry (Gilabert et al. 2015; Dondeti and Tippur, 2022). The stress concentration amplifies the applied stresses, facilitating crack propagation. High-stress concentrations can arise at structural discontinuities, such as notches, joints and corners, leading to localised crack growth.

Aggregate Interlock: Aggregates in concrete provide mechanical interlocking effects that resist crack propagation (Struble et al. 1980; He et al. 2017). The irregular shape and rough surface texture of aggregates create interfacial friction, impeding crack growth (Akacoglu, 2017). However, under high stress levels, cracks can propagate through weakened interfaces between the cement paste and aggregates, resulting in crack progression.

Fracture Toughness: Fracture toughness characterises a material's resistance to crack propagation. In concrete, fracture toughness depends on factors such as the properties of the cementitious matrix, aggregate characteristics and the presence of supplementary materials like fibres or additives (Prokopski and Langier, 2000; Lin and Karadelis, 2019; Dehestani et al. 2020). Higher fracture toughness reduces the susceptibility of concrete to crack propagation.

Microcracking and Microstructural Damage: Concrete experiences microcracking at different length scales due to various mechanisms. These microcracks can form between cement particles, within the cement paste, and at interfaces between the cement paste and aggregates (Ringot and Bascoul, 2001; Mac et al. 2021). Over time, these microcracks can coalesce and propagate, leading to visible cracks. Microstructural damage, such as aggregate debonding, matrix cracking and interface degradation, can also contribute to crack propagation.

Environmental Effects: Environmental factors play a significant role in crack propagation. Freeze-thaw cycles subject concrete to repeated cycles of expansion and contraction, inducing internal stresses and microcracking (Yang et al. 2006; Pilehvar et al. 2019). Chemical exposure from substances like de-icing salts or aggressive chemicals can degrade the concrete matrix, reducing its resistance to crack growth. Additionally, cyclic loading, such as repeated traffic loads on pavements, can gradually propagate existing cracks or initiate new ones.

Understanding crack initiation and propagation mechanisms in concrete allows engineers and researchers to develop strategies for crack prevention and control. Improved mix designs, the addition of reinforcing fibres or supplementary materials, proper curing techniques and structural design considerations can enhance crack resistance and prolong the service life of concrete structures. Advanced monitoring techniques, such as acoustic emission testing and digital image correlation, enable the real-time assessment of crack development and behaviour, facilitating proactive maintenance and repair.

2.3 Types of Fracture in Concrete

Fractures in concrete can exhibit various characteristics and mechanisms, reflecting the complex behaviour of the material under different loading conditions. Understanding the types of fracture in concrete is crucial for assessing the structural integrity, identifying potential failure modes and implementing appropriate preventive measures.

Tensile fractures in concrete occur when the tensile stresses exceed the concrete's tensile strength. These fractures can take the form of localised cracks, such as surface cracks or cracks near stress concentrations, or distributed cracks that propagate throughout the structure (Van Mier et al. 2003; Guo et al. 2022). The initiation and propagation of tensile fractures are influenced by various factors. The material properties of concrete, such as its tensile strength and fracture toughness, play a crucial role in determining the susceptibility to fracture (Kang et al. 2010; Dutler et al. 2018). The loading conditions, including the magnitude and distribution of applied loads, can also affect the initiation and propagation of cracks. Additionally, the presence of reinforcing elements, such as steel reinforcement or fibre reinforcement, can significantly influence the behaviour of tensile fractures in concrete.

Shear fractures in concrete result from the sliding or tearing of the material along planes of weakness due to shear forces. These fractures commonly occur near supports, joints, or other areas of structural discontinuity where shear stresses are concentrated. The occurrence and propagation of shear fractures depend on several factors. The shear span-to-depth ratio of the structural member plays a significant role, with higher ratios generally leading to increased vulnerability to shear failure (Sanal, 2020; Mak and Lees, 2023). The detailing and spacing of shear reinforcement, such as stirrups or shear links, can also influence the behaviour of shear fractures (Monney et al. 2023; Sarkar et al. 2023). Furthermore, the presence of construction joints, cracks, or other structural irregularities can provide potential paths for shear failure (Wang, 2010).

Flexural fractures occur in structural elements subjected to bending moments, such as beams or slabs. These fractures typically develop along the tension side of the member due to the tensile stresses induced by bending. The formation and propagation of flexural fractures are influenced by several factors. The loading conditions, including the magnitude and distribution of bending moments, can affect the development and extent of flexural cracks (Cesar Bastos et al. 2017; Zhu et al. 2020). The geometry of the member, such as its depth, width, and span length, can also influence the behaviour of flexural fractures (Borosnyói and Balázs, 2005; Nguyen et al. 2013). Additionally, the presence and detailing of reinforcement, such as tension reinforcement at the bottom of beams or slabs, can contribute to the resistance against flexural cracking.

Compression fractures in concrete are characterised by the crushing or spalling of the material under excessive compressive forces. These fractures often occur in columns, footings, or other elements subjected to high compressive loads. The occurrence and behaviour of compression fractures depend on various factors. The compressive strength of the concrete is a critical parameter, as higher strength concrete exhibits greater resistance to compression fractures. The confinement of the concrete, either through confinement reinforcement or structural confinement provided by adjacent elements, can also influence the resistance to compression failure (Cusatos et el. 2006; Wang et al. 2021). Furthermore, the presence of reinforcement, such as vertical reinforcement in columns, can contribute to the overall strength and stability of the element.

Impact fractures in concrete are a result of sudden and high-energy loads, such as collisions or dynamic events. These fractures often lead to localised cracks and fragmentation of the concrete due to the rapid and intense forces involved. The behaviour of concrete under impact loading depends on various factors. The compressive strength, tensile strength and fracture toughness of the concrete play significant roles in determining its response to impact loads. The strain rate at which the impact occurs can also influence the behaviour, with higher strain rates often leading to increased brittleness and reduced energy absorption capacity (Mindess and Bentur, 1985; Guo et al. 1995; Shin et al. 2022). Additionally, the presence of reinforcement or other energy-absorbing mechanisms, such as fibre reinforcement or damping devices, can enhance the impact resistance of concrete structures.

Fatigue fractures in concrete develop over time under repeated or cyclic loading. These fractures typically initiate from microscopic cracks and gradually propagate, leading to structural failure if not properly addressed. The occurrence and progression of fatigue cracks are influenced by several factors (Bazant and Xu, 1991; Subramaniam et al. 2002; Jia et al. 2023). The loading frequency, or the number of loading cycles applied over a given time period, can affect the rate of crack initiation and propagation (Keerthana and Kishen, 2021). The stress amplitude, which represents the range of stresses experienced by the structure during each loading cycle, is a critical factor in fatigue crack growth. Material properties, such as the fatigue strength and crack growth resistance of the concrete, also play significant roles in determining the susceptibility to fatigue failure (Li and Matsumoto, 1998). Additionally, the presence of stress concentrations, such as notches, joints, or irregularities in the structure, can promote the initiation and growth of fatigue cracks.

Understanding the different types of fractures in concrete and their underlying mechanisms is essential for engineers to mitigate cracking, enhance durability and optimise the design and construction of concrete structures. This knowledge helps in selecting appropriate materials, reinforcement strategies, and maintenance practices to ensure long-term performance and safety. By controlling crack formation and propagation, engineers can improve the overall performance of concrete structures, minimise the ingress of harmful agents and optimise the design for effective load-carrying capacity. Additionally, understanding fracture mechanisms aids in the development of maintenance practices and repair strategies, ensuring the longevity and safety of existing concrete structures.

2.4 Factors Influencing Fracture Propagation

Fracture propagation in concrete is influenced by various factors that can significantly impact the behaviour and integrity of the material. Understanding these factors is crucial for predicting and managing crack growth in concrete structures. Some key factors influencing fracture propagation in concrete include:

1. Material Properties: The mechanical properties of concrete, such as its tensile strength, modulus of elasticity, fracture toughness and stiffness, play a vital role in fracture propagation. Concrete with higher tensile strength and fracture toughness tends to exhibit better resistance to crack propagation (Kim et al. 2015; Dastgerdi et al. 2019). Additionally, the presence of aggregates, admixtures and other additives can affect the fracture behaviour of concrete by altering its mechanical properties.

2. Loading Conditions: The magnitude, type and duration of applied loads have a significant influence on crack propagation in concrete (Dzik and Lajtai, 1996). Different loading conditions, such as static, cyclic, impact, or dynamic loading, induce varying stress states that affect crack initiation and growth (Yang et al. 2020). High-stress concentrations and rapid loadings can accelerate crack propagation, leading to sudden failures. Fatigue loading, in particular, can cause progressive crack growth over time.

3. Structural Design: The design of concrete structures, including the arrangement and detailing of reinforcement, can influence crack propagation. Proper reinforcement placement and detailing can help distribute loads and reduce localised stress concentrations, thereby inhibiting crack growth. On the other hand, inadequate reinforcement, improper joint design, or inadequate structural connections can promote crack initiation and propagation (Słowik, 2019).

4. Environmental Conditions: Environmental factors, such as temperature variations, moisture, chemical exposure and freeze-thaw cycles, can impact fracture propagation in concrete (Larosche, 2009). Temperature changes can induce thermal stresses, while exposure to aggressive chemicals or moisture can lead to chemical reactions and degradation of the material, making it more susceptible to cracking. Freeze-thaw cycles can cause internal pressure build-up and microcracking (Rhardane et al. 2021).

5. Construction Practices: The quality of construction practices significantly affects the resistance of concrete to crack propagation. Adequate curing, consolidation and compaction of concrete are essential to ensure proper bonding and minimise voids and weak zones. Inadequate curing or improper construction techniques can result in weak regions, poor bonding, or voids, which can serve as sites for crack initiation and propagation (Laefer et al. 2010; Dao et al. 2014).

6. Age and Degradation: The age of the concrete and its long-term exposure to environmental and loading conditions can influence fracture propagation (Wittmann, 1985; Giaccio et al. 2008). Concrete undergoes aging and degradation processes, such as shrinkage, creep, carbonation and alkali-silica reaction, which can weaken the material and increase its susceptibility to cracking. Aging can lead to changes in material properties and the formation of microcracks, facilitating crack propagation.

7. Size and Shape of Specimen: The size and shape of the concrete specimen or structural element can impact fracture propagation (Wittmann et al. 1990; Kim et al. 2009; Kumar and Barai, 2012). Larger or thicker sections tend to experience higher stress concentrations, leading to more pronounced crack propagation. The presence of notches, corners, or other stress concentrators can also promote crack initiation and growth.

8. Stress Concentrations: The presence of stress concentrators, such as notches, joints, or irregularities, can significantly affect crack propagation (Gao et al. 2020; Zhang et al. 2023). Stress concentrations amplify the local stresses, making those regions more prone to crack initiation and subsequent propagation. It is crucial to consider stress concentration factors and mitigate their effects during the design and construction stages to minimise crack propagation risks.

By considering and analysing factors such as concrete mix components, proportioning, compressive strength, fibre reinforcement and environmental conditions, engineers can design and implement strategies to control crack propagation in concrete structures. They can select suitable materials, optimise reinforcement design and employ effective construction practices to enhance the structural integrity and durability. Understanding the fracture parameters and behaviour of concrete under different loading conditions enables engineers to develop techniques for crack prevention and mitigation. Moreover, considering environmental conditions throughout the service life of the structure helps in identifying potential risks and implementing appropriate maintenance practices to minimise crack formation and ensure long-term performance and safety.

3. Experimental Techniques for Studying Fracture Propagation

Experimental techniques play a crucial role in studying fracture propagation in concrete, allowing researchers to gain insights into the behaviour and mechanics of cracks. Several techniques are employed to investigate crack initiation, propagation and associated parameters.

3.1 Non-Destructive Testing Methods

Non-destructive testing methods are valuable for studying fracture propagation in concrete without causing damage. Techniques such as Acoustic Emission (AE) Technique, Ultrasonic Testing and Digital Image Correlation (DIC) provide valuable insights into crack detection, localisation and monitoring. These methods enable the evaluation of fracture behaviour and structural integrity in a non-invasive manner.

3.1.1 Acoustic Emission (AE) Technique

Scientifically defined, acoustic emission is a phenomenon of sound and ultrasound wave generation by materials that undergo deformation and fracture processes (Fig. 1). The Acoustic Emission (AE) technique is a valuable tool for studying fracture propagation in concrete structures. AE involves the detection and analysis of transient stress waves or acoustic signals generated by the microcracking and fracture processes within the material. It provides real-time information on the initiation, growth and propagation of cracks, offering insights into the structural behaviour and integrity of concrete. The AE technique is non-destructive and can be applied during the testing of concrete specimens or in-service monitoring of existing structures. It involves the use of sensitive sensors or transducers that detect and record the high-frequency acoustic signals generated by crack formation and propagation. These signals are then processed and analysed to characterise the fracture behaviour of the concrete.

By monitoring the AE signals, engineers can gain information on the crack initiation threshold, crack growth rates, and the spatial distribution of cracks within the concrete. This data can help in understanding the mechanisms of fracture propagation, identifying critical regions prone to cracking, and assessing the structural performance under different loading conditions. The AE technique is particularly useful for evaluating the behaviour of concrete under dynamic or cyclic loading, such as impact or fatigue loading. It allows for the detection of crack initiation at an early stage, enabling timely preventive measures and maintenance interventions to avoid catastrophic failures. Moreover, AE can be used to assess the effectiveness of crack repair techniques or the performance of fibre reinforcement in inhibiting crack propagation. It provides a means to validate the efficacy of these interventions and optimises their design for enhanced structural performance.

The use of acoustic emission (AE) technique in studying the fracture of concrete has been explored in several research studies. Rossi et al. (1990) highlighted the applicability of AE in fracture mechanics applied to concrete. They discussed the relationship between AE parameters and crack propagation, emphasizing the potential of AE in monitoring crack growth in concrete structures. Grosse et al. (1997) focused on the localization and classification of fracture types in concrete using quantitative AE measurement techniques. They demonstrated the ability of AE to identify different fracture modes and distinguish between different types of cracks, enhancing the understanding of concrete fracture mechanisms.

Landis and Baillon (2002) conducted experiments to correlate AE energy with fracture energy of concrete. Their findings provided insights into the relationship between AE energy and the mechanical properties of concrete, contributing to the development of AE-based fracture energy evaluation methods. Grosse and Finck (2006) proposed a quantitative evaluation method for fracture processes in concrete using signal-based AE techniques. They discussed the potential of AE to characterize crack evolution and quantitatively assess the damage progression in concrete structures. Shah and Kishen (2010) investigated the fracture behaviour of the concrete-concrete interface using the AE technique. Their study demonstrated the effectiveness of AE in monitoring crack initiation, propagation, and closure at the interface, providing valuable information for interfacial bond strength assessment. Hu et al. (2013) evaluated concrete fracture procedures based on AE parameters. They discussed the correlation between AE signals and crack growth stages, suggesting that AE monitoring can be used to assess the fracture process and estimate the remaining life of concrete structures.

Other studies, such as Ohno and Ohtsu (2010), Aggelis et al. (2011), Sagar and Prasad (2011) explored crack classification, specific fracture energy measurement, cracking evolution analysis and classification of cracking modes using AE parameters. These studies demonstrated the potential of AE in characterizing different aspects of concrete fracture behaviour. Furthermore, Alam et al. (2014), Farnam et al. (2015), and Chen et al. (2020) investigated various aspects of AE waveform characterisation, such as crack origin, mode identification and loading rate effects on concrete fracture behaviour. These studies highlighted the capabilities of AE in providing detailed information on crack characteristics and behaviour. The study by Banjara et al. (2019) delves into the experimental exploration of cracking evolution in concrete and cement mortar through the application of the Acoustic Emission (AE) technique. Their research specifically focuses on understanding AE parameters throughout the damage progression in both shear deficient and Glass Fiber Reinforced Polymer (GFRP) strengthened reinforced concrete components. The investigation provides valuable insights into the dynamic nature of cracking in these materials, contributing to advancements in structural health monitoring and maintenance strategies.

One aspect to consider is the interpretation and analysis of AE signals. AE signals can be influenced by various factors, including background noise, sensor placement, and signal attenuation. These factors can introduce uncertainties and affect the accuracy of crack detection, localisation and characterisation. Standardised methodologies and signal processing techniques are essential for consistent and reliable interpretation of AE data. Further research is needed to develop robust analysis procedures that minimise the impact of noise and enhance the accuracy of AE-based fracture assessment. Additionally, the relationship between AE parameters and fracture properties of concrete is complex and may vary depending on several factors, such as concrete mix composition, specimen size, and loading conditions. While some studies have attempted to correlate AE energy with fracture energy or crack size, there is still a need for a deeper understanding of the fundamental relationships and the influence of confounding variables. Improved methodologies for calibrating AE parameters and establishing reliable correlations with fracture properties would enhance the accuracy and applicability of AE technique in concrete fracture analysis.

Furthermore, the applicability of AE technique to different types of concrete structures and real-world scenarios needs to be thoroughly examined. Most of the cited studies focus on laboratory-scale specimens or simplified configurations, which may not fully capture the complexities of concrete structures in the field. Investigating the practicality and reliability of AE technique in real-world settings, such as large-scale structures or complex geometries, would strengthen the confidence in its applicability and effectiveness. Another consideration is the integration of AE with other non-destructive testing (NDT) techniques or imaging methods. Combining AE with techniques like digital image correlation or ultrasonic testing can provide complementary information on crack evolution, propagation patterns, and internal damage. The integration of multiple NDT techniques could enhance the accuracy and comprehensive understanding of concrete fracture behaviour. Moreover, the potential impact of environmental conditions on AE measurements and the long-term performance of AE sensors should be carefully evaluated. Factors such as temperature, humidity and aging of sensors can influence AE data quality and the reliability of long-term monitoring. Adequate sensor calibration, sensor maintenance and monitoring protocols are crucial to ensure the accuracy and consistency of AE measurements over time.

3.1.2 Ultrasonic Testing

Ultrasonic testing is a widely used NDT technique for studying fractures in concrete. This technique involves the propagation of high-frequency sound waves through the material and analysing their interaction with internal defects, such as cracks or voids. By measuring the time it takes for the sound waves to travel through the concrete and analysing the reflected or transmitted signals, valuable information about the presence, location and extent of fractures can be obtained.

Ultrasonic testing allows for the assessment of both the size and orientation of cracks, as well as the determination of their depth within the concrete. The technique is particularly effective in detecting fine cracks that may not be visible to the naked eye, enabling early detection of potential structural issues and preventing further deterioration. Moreover, by monitoring changes in the ultrasonic signals over time, engineers can assess the stability and progression of fractures, facilitating proactive maintenance and repair strategies. The advantages of ultrasonic testing for fracture evaluation in concrete include its non-destructive nature, high sensitivity to small cracks, and ability to provide quantitative measurements. Additionally, it can be performed on-site, making it a convenient tool for field inspections and structural assessments. However, it is important to consider factors such as concrete composition, moisture content, and surface conditions, as they can affect the accuracy and reliability of the results.

Ultrasonic testing has been widely used to study fractures in concrete, and several research studies have explored its effectiveness and limitations. Prassianakis and Giokas (2003) examined the mechanical properties of old concrete using destructive and non-destructive ultrasonic testing methods. Their findings highlighted the potential of ultrasonic testing in assessing concrete quality and identifying internal flaws. Similarly, Prassianakis and Prassianakis (2004) focused on ultrasonic testing of non-metallic materials, including concrete and marble, emphasizing its applicability in fracture mechanics. Stauffer et al. (2005) investigated nonlinear ultrasonic testing for early damage detection in concrete. They explored resonant and pulse velocity parameters and concluded that nonlinear ultrasonic methods offer valuable insights into concrete deterioration. Zhao et al. (2006) conducted an experimental study on ultrasonic wave attenuation across parallel fractures, shedding light on fracture characterization using ultrasonic techniques. Shiotani et al. (2009) presented a case study on the global monitoring of large concrete structures using acoustic emission and ultrasonic techniques. Their research demonstrated the effectiveness of combining these methods for structural health assessment. Shah and Ribakov (2010) evaluated the effectiveness of nonlinear ultrasonic and acoustic emission evaluation in concrete with distributed damages, emphasizing the advantages of nonlinear ultrasonic testing in detecting and assessing damage in concrete structures.

Iyer et al. (2012) focused on the evaluation of ultrasonic inspection and imaging systems for concrete pipes. Their research highlighted the potential of these systems in providing accurate and reliable information on concrete pipe conditions. More recently, Rucka et al. (2021) investigated the characterization of the fracture process in polyolefin fibre-reinforced concrete using ultrasonic waves and digital image correlation. Their study demonstrated the applicability of ultrasonic testing in assessing fracture behaviour and monitoring the crack propagation process. The study conducted by Kaur et al. (2019) focused on the application of ultrasound testing for studying fractures in concrete. The research explores the concept of healing and simultaneous ultrasonic monitoring of cracks in concrete. The authors investigated the effectiveness of ultrasound techniques in detecting and monitoring cracks in real-time, with a particular emphasis on the healing process. The findings of the study provide insights into the potential of ultrasound testing as a non-destructive method for assessing crack propagation and healing in concrete structures. The results are summarised in Fig. 3

The critical analysis of the use of ultrasonic testing to study fractures in concrete reveals both strengths and limitations in its application. Ultrasonic testing offers several advantages, including its non-destructive nature, ability to assess mechanical properties, detect damage, and characterise fracture behaviour in concrete structures. One strength is its potential for evaluating the mechanical properties of old concrete and non-metallic materials, as demonstrated in some studies. This can provide valuable insights into the quality and condition of existing structures. Additionally, the use of nonlinear ultrasonic testing shows promises for early damage detection in concrete. However, there are limitations to consider. The practical implementation and reliability of nonlinear ultrasonic testing require further investigation and validation in real-world scenarios. The generalisability of findings may also be limited due to the focus on specific fracture configurations or concrete structures.

The combination of ultrasonic testing with other techniques, such as acoustic emission or digital image correlation, shows potential for global monitoring or fracture characterisation. However, scalability, practical implementation and broader applicability need to be carefully assessed and validated. Furthermore, the effectiveness of ultrasonic inspection and imaging systems for concrete pipes may be subject to limitations, such as potential false positives or the requirement for skilled operators. These limitations should be addressed to enhance the reliability and practicality of ultrasonic testing in concrete pipe inspection.

Overall, while ultrasonic testing offers significant potential for studying fractures in concrete, it is essential to acknowledge its limitations, including limited penetration depth, potential interference from heterogeneous materials and the need for further research, standardisation, and validation. Addressing these challenges will enhance the reliability and practical utilisation of ultrasonic testing for fracture analysis in concrete structures.

3.1.3 Digital Image Correlation (DIC)

Digital Image Correlation (DIC) has become an increasingly popular technique for analysing fracture behaviour in concrete structures. DIC allows for non-contact, full-field measurements of surface deformations and strain fields, providing valuable insights into crack initiation, propagation, and failure mechanisms (Corr et al., 2007; Wu et al., 2011). One significant advantage of DIC is its ability to capture the complete displacement and strain fields over the concrete surface, enabling researchers to observe and quantify local deformations with high spatial resolution (Fayyad & Lees, 2014). This capability allows for a comprehensive understanding of crack development, including crack nucleation, growth and interaction (Fayyad & Lees, 2017).

Several studies have utilized DIC to investigate specific aspects of fracture behaviour in concrete. For instance, Corr et al. (2007) employed DIC to analyse interfacial debonding properties in concrete, providing valuable insights into crack initiation and propagation at the interfaces. Wu et al. (2011) conducted an experimental investigation on fracture process zones (FPZ) in concrete using DIC, examining the size and evolution of the FPZ under different loading conditions. These studies highlight the usefulness of DIC in understanding fundamental fracture phenomena in concrete. DIC has also been applied to study the fracture properties of various types of concrete, such as reinforced concrete (Fayyad & Lees, 2014), geopolymer concrete (Xie et al., 2017) and fibre-reinforced concrete (Bhosale & Prakash, 2020). These studies have provided valuable insights into the influence of different materials and reinforcement configurations on crack initiation and propagation, contributing to the development of more durable and resilient concrete structures.

In the study conducted by Bhosale and Prakash (2020), DIC was employed to analyse crack propagation in different types of concrete beams: synthetic, steel-reinforced, and hybrid fibre-reinforced. DIC allowed for the measurement of full-field displacements and strains on the beam surfaces, providing valuable insights into crack initiation, growth and propagation patterns. The use of DIC enabled the researchers to quantify crack widths and accurately track crack propagation paths, facilitating a comprehensive understanding of the fracture behaviour and performance of the different concrete beam types. This study exemplifies the utility of DIC in investigating crack propagation and its variation in different concrete materials and reinforcement configurations. The Comparison of DIC results with experimental results from clip gauge readings for CTOD: (a) HB75 beam, (b) PO75 beam is shown in Fig. 4.

Despite its benefits, DIC does have some limitations that must be considered. One crucial aspect is the surface preparation and the application of contrasting patterns or markers on the concrete surface. Inaccurate or unstable patterns can lead to measurement errors and affect the reliability of the results (Huang et al., 2019). The complexity of concrete materials, including their heterogeneity, anisotropy, and time-dependent behaviour, poses challenges for accurately interpreting DIC data. It requires careful consideration of material models and the incorporation of appropriate constitutive relationships (Golewski, 2019). It is important to note that DIC primarily captures surface deformations and may not fully represent internal crack development. While it provides valuable information about surface displacements and strain fields, complementary techniques such as X-ray computed tomography or acoustic emission may be necessary to investigate the internal crack behaviour and its influence on the overall fracture process (Fayyad & Lees, 2014). Another consideration is the influence of environmental conditions and loading configurations on concrete behaviour and DIC measurements. Factors such as temperature, humidity and loading rate can affect the material response and the accuracy of DIC measurements. Therefore, careful control and monitoring of these parameters are crucial to ensure the validity of the experimental results (Wu et al., 2011).

In summary, DIC is a valuable tool for studying fracture behaviour in concrete structures. It provides full-field measurements of surface deformations and strain fields, allowing for a comprehensive understanding of crack development and failure mechanisms. However, the limitations associated with surface preparation, material complexity, internal crack monitoring and environmental influences should be carefully considered to ensure accurate and reliable analysis of fracture in concrete.

3.2 Destructive Testing Methods

Destructive testing methods play a crucial role in studying fracture behaviour in concrete. These methods involve subjecting concrete specimens to controlled loading conditions until failure occurs, allowing researchers to analyse fracture mechanics and understand the material's response to external forces. Techniques such as three-point bending, four-point bending, and direct tension tests are commonly employed to evaluate properties like flexural strength, fracture toughness, and crack propagation behaviour. Destructive testing provides valuable information on the critical crack size, energy absorption capacity and failure modes of concrete. By assessing the fracture characteristics through destructive tests, engineers and researchers can enhance concrete design, develop more durable structures and improve construction practices.

3.2.1 Three-Point Bending Test

The Three-Point Bending Test is a commonly employed method for investigating fracture behaviour in concrete materials. Several studies have utilized this test to gain insights into the fracture properties and mechanical behaviour of concrete. One of the key advantages of the Three-Point Bending Test is its simplicity and ease of implementation. The test involves applying a load to a notched or unnotched concrete specimen supported at two points while measuring the resulting deflection and load. This provides valuable information on the crack initiation and propagation, fracture toughness and energy absorption capacity of concrete (Qiao & Xu, 2004; Sun et al., 2019; Li et al., 2019). The studies reviewed demonstrate the versatility and applicability of the Three-Point Bending Test in various contexts. For instance, researchers have used this test to evaluate the fracture energy of composite-concrete interfaces (Qiao & Xu, 2004), assess the performance of fibre-reinforced concrete (Sun et al., 2019), and investigate the influence of recycled aggregates on fracture behaviour (Li et al., 2019).

However, it is important to acknowledge certain limitations associated with the Three-Point Bending Test. The test primarily provides information on the fracture behaviour under specific loading conditions and specimen geometries. The simplified test setup may not fully capture the complex stress state present in real-world structural elements, potentially leading to discrepancies between laboratory results and field performance (Abdalla & Karihaloo, 2003). Furthermore, the interpretation of Three-Point Bending Test results requires careful consideration of factors such as specimen size, shape and boundary conditions. The assumptions made in the analysis, such as linear elastic behaviour and plane stress conditions, may not always reflect the true response of concrete structures under complex loading conditions (Yin et al., 2020; Tang et al., 2022).

Overall, the Three-Point Bending Test serves as a valuable tool for studying fracture in concrete. It offers a practical and accessible approach to evaluate fracture properties and understand the mechanical behaviour of concrete materials. However, researchers should be aware of the inherent limitations and ensure that test conditions align with the intended application to obtain reliable and meaningful results (Zhang et al., 2022; Chen et al., 2014; Ohno et al., 2014)

3.2.2 Compact Tension Test

The Compact Tension Test has been widely adopted as a valuable method for investigating fracture behaviour in concrete materials. In a Compact Tension Test (CTT), a small, standardized specimen of concrete is subjected to controlled loading in a way that induces a crack to propagate through the material. This test allows researchers and engineers to analyse key fracture parameters, such as critical stress intensity factors and crack growth rates, which are essential for understanding the material's resistance to fracture and its overall durability. The CTT involves applying a load to a notched specimen, typically in the form of a compact tension (CT) geometry. The specimen's response to the applied load, particularly the initiation and propagation of cracks, is carefully monitored and analysed. The data obtained from the test can be used to characterize the material's fracture toughness, a critical property that influences its structural performance and reliability.

It offers a controlled and standardized approach to studying crack propagation, fracture toughness, and other fracture parameters. Xu and Reinhardt (1999) focused on determining the double-K criterion for crack propagation in quasi-brittle fracture using compact tension and wedge splitting specimens. By analysing the experimental results, they provided insights into the relationship between crack growth and applied load, as well as the influence of specimen geometry and loading conditions. This research contributed to the understanding of fracture criteria in concrete. Kumar and Barai (2009) expanded on the determination of double-K fracture parameters for concrete using weight function methods. Their study explored the application of these methods to both compact tension and wedge splitting tests, enabling a more comprehensive understanding of fracture behaviour. By considering the weight functions, they were able to accurately assess the fracture parameters, enhancing the reliability of the test results.

Ožbolt, Sharma, and Reinhardt (2011) delved into the dynamic fracture behaviour of concrete in compact tension specimens. They conducted experiments to investigate the effect of strain rate on crack propagation and fracture toughness. The dynamic nature of concrete fracture is an important consideration, especially in situations where high strain rates are involved, such as in impact or seismic events. This research provided valuable insights into the behaviour of concrete under dynamic loading conditions. Building upon the work of Ožbolt et al. (2011), Ožbolt, Bošnjak, and Sola (2013) carried out a combined experimental and numerical study on dynamic fracture behaviour in concrete compact tension specimens. Their research provided a comprehensive analysis of crack propagation, including the effects of loading rate and specimen size. By integrating experimental data with numerical simulations, they enhanced the understanding of dynamic fracture behaviour and its applicability to real-world situations. Cifuentes et al. (2017) introduced a modified disk-shaped compact tension test to measure concrete fracture properties. Recognising the limitations of traditional compact tension specimens, they proposed a modified specimen geometry that aimed to improve the accuracy and reliability of fracture data. This innovation highlights the ongoing efforts to refine and optimise testing techniques to better capture the fracture behaviour of concrete.

While the Compact Tension Test offers numerous advantages, it is crucial to acknowledge certain limitations. The interpretation of test results requires careful consideration of factors such as specimen size, shape, boundary conditions and loading rates. The dynamic behaviour of concrete, which may significantly differ from its quasi-static behaviour, needs to be addressed to better understand fracture under high strain rates. Additionally, the transferability of test results to real-world structural elements should be approached with caution, as the simplified laboratory conditions may not fully capture the complexities of field applications.

3.2.3 Brazilian Test

The Brazilian Test is a widely utilised method for studying fracture behaviour in concrete materials. It involves applying compressive loads to a disc-shaped specimen and measuring the resulting tensile stresses along the diametrical plane. This test provides valuable insights into the tensile strength, fracture toughness, and other fracture properties of concrete. Several studies have focused on investigating various aspects of the Brazilian Test and its application in understanding concrete fracture. Rocco et al. (1999) conducted experimental investigations to verify the size effect and boundary conditions in the Brazilian Test. Their research highlighted the importance of specimen size and loading geometry on the measured fracture properties.

López et al. (2008) conducted a meso-structural study using interface elements to analyse concrete fracture in the Brazilian Test under compression, biaxial and uniaxial loading conditions. Their research provided insights into the crack propagation mechanisms and the influence of loading configurations on fracture behaviour. García et al. (2017) reviewed and provided new insights into the Brazilian Test for concrete specimens subjected to different loading geometries. Their study explored the effects of specimen geometry, loading rate and boundary conditions on fracture behaviour, highlighting the importance of considering these factors in test design and interpretation. Khosravani et al. (2018) focused on fracture studies of ultra-high-performance concrete using dynamic Brazilian tests. They investigated the dynamic response of concrete under high strain rates and explored the fracture behaviour of this advanced material. Their research demonstrated the applicability of the Brazilian Test in characterizing the fracture properties of high-performance concretes.

Other studies have also investigated specific aspects of the Brazilian Test. Rastiello et al. (2018) studied the effect of crack opening on the intrinsic permeability of localized macro-cracks in concrete samples, while Sun and Wu (2021) analysed crack initiation and source mechanisms based on moment tensor analysis. Ren et al. (2022) investigated the damage mechanism of concrete in both the Brazilian Test and the flattened Brazilian Test, utilising moment tensor analysis to gain insights into the fracture process. Furthermore, Padilla et al. (2022) focused on monitoring post-peak crack propagation in concrete during the Brazilian Tension Test. They proposed a monitoring technique to capture crack growth behaviour and assessed its potential for evaluating fracture properties and structural performance.

The Brazilian Test offers several advantages for studying concrete fracture, including its simplicity, applicability to various concrete types, and controlled stress distribution. However, it is essential to consider certain limitations, such as the influence of specimen geometry, size effect and loading rate. Additionally, the interpretation of test results should account for the inherent complexities of concrete behaviour and the specific conditions under which the test is conducted.

3.3 Novel Experimental Techniques

The use of novel experimental techniques such as X-ray tomography, digital volume correlation (DVC) and scanning electron microscopy (SEM) has significantly advanced the understanding of fracture behaviour in concrete. These techniques have revolutionised the ability to study concrete fracture at the microstructural level, leading to improved knowledge of fracture mechanisms and paving the way for enhanced design and construction practices.

3.3.1 X-ray Tomography

The use of X-ray tomography has emerged as a valuable tool for studying fracture behaviour in concrete, attracting considerable attention from researchers in recent years. This non-destructive imaging technique has been employed in numerous studies, aiming to explore various aspects of concrete fracture, such as crack propagation, damage evolution and fracture mechanics parameters. X-ray tomography enables researchers to visualise the internal structure of concrete and track the development of cracks with exceptional detail and precision (De Wolski et al., 2014; Ren et al., 2015). By capturing three-dimensional images of the fracture process, it provides valuable insights into fundamental aspects such as crack initiation, propagation paths, and interactions with aggregate particles and other constituents of the material (Huang et al., 2015; Skarżyński & Tejchman, 2016).

The study by Ríos et al. (2019) highlights the use of X-ray tomography in analysing the tensile fracture properties of ultra-high-strength fibre-reinforced concrete (UHSFRC) with different types of steel fibres. By employing X-ray tomography, the researchers were able to visualise the internal structure of the UHSFRC specimens and track the progression of cracks during tensile testing. This non-destructive imaging technique provided valuable insights into the fracture behaviour, crack initiation, and crack propagation mechanisms in UHSFRC. The findings from this study demonstrate the effectiveness of X-ray tomography in characterizing the fracture properties of advanced concrete materials, facilitating a deeper understanding of their mechanical performance. Figure 5 shows some images obtained with the X-ray CT for each mix. The red spherical shaped volumes represent the pores and the golden lines represent the steel fibres.

One significant application of X-ray tomography in the field of concrete fracture research is the development of meso-scale fracture models. By integrating X-ray computed tomography (CT) data with numerical simulations and damage models, researchers can accurately predict crack patterns and analyse fracture behaviour (Huang et al., 2015; Huang et al., 2016; Trawiński et al., 2018). This integration facilitates a deeper understanding of fracture mechanisms and assists in the design of more durable and resilient concrete structures. However, it is essential to acknowledge the limitations of X-ray tomography. Factors such as resolution and imaging capabilities can vary, influencing the level of detail that can be captured (du Plessis & Boshoff, 2019). Moreover, interpreting X-ray CT images requires expertise in image analysis and processing techniques (Suzuki et al., 2017).

Despite the challenges, the use of X-ray tomography has significantly contributed to advancing the understanding of concrete fracture behaviour. By providing experimental data and visualizing the internal structure, this technique has shed light on the mechanisms of crack propagation and the influence of material properties on fracture (De Wolski et al., 2014; Ren et al., 2015; Yang et al., 2017). Continued advancements in X-ray tomography technology and analysis techniques hold promise for further expanding its potential in studying fracture phenomena in concrete (Kong et al., 2020).

3.3.2 Digital Volume Correlation (DVC)

Digital Volume Correlation (DVC) has emerged as a valuable technique for studying fracture in concrete, particularly when combined with X-ray computed tomography (CT) imaging. The use of DVC in analysing interior fracture behaviour of rubber-cement composites (Hong et al., 2020) and cement-based materials subjected to loading (Lorenzoni et al., 2022) has provided valuable insights into the deformation and strain fields within the materials. One advantage of DVC is its ability to capture full-field displacements and strains within a volume of interest, enabling a detailed understanding of crack initiation, propagation and interaction with the surrounding material. This information is crucial for assessing the structural integrity and performance of concrete under different loading conditions. Li et al. (2023) conducted a study focusing on localised damage analysis of cement mortar using in-situ compressive loading and DVC. By capturing detailed three-dimensional images (Fig. 6) and quantifying displacement and strain fields, the researchers gained insights into microstructural changes and damage evolution. The study highlights the potential of DVC for understanding fracture mechanisms and aiding in the development of predictive tools.

However, the application of DVC to study concrete fracture is not without challenges. The accuracy of DVC results relies heavily on the quality of the image data and the selection of appropriate correlation algorithms. The complex microstructure of concrete, including the presence of aggregates and cracks, can pose difficulties in achieving accurate and reliable displacement and strain measurements. Additionally, the computational requirements for processing large datasets generated by DVC analysis can be significant, making it time-consuming and computationally demanding. Furthermore, the interpretation of DVC results requires careful consideration and validation, as the accuracy of the obtained displacement and strain fields is influenced by factors such as noise, image resolution and boundary conditions.

Despite these challenges, the use of DVC in combination with X-ray CT imaging has demonstrated its potential for enhancing the understanding of concrete fracture mechanisms. By providing detailed and quantitative information on crack evolution and deformation, DVC contributes to the development and validation of fracture models, improving the prediction and design of concrete structures.

3.3.3 Scanning Electron Microscopy (SEM)

Scanning Electron Microscopy (SEM) has been widely used as a valuable tool for studying the fracture behaviour of concrete. Researchers have employed SEM techniques to investigate various aspects of concrete fracture, providing insights into microstructural features, crack propagation and failure mechanisms. One of the key advantages of SEM is its high-resolution imaging capability, which allows for the visualisation of microcracks and the examination of fracture surfaces at a detailed level (Ollivier, 1985; Nemati, 1997). By using SEM, researchers can observe the microcracks and defects in the concrete matrix, providing valuable information about the initiation and propagation of cracks (Bisschop & Van Mier, 2002). SEM analysis also enables the characterisation of the interfacial transition zone (ITZ) microcracking and its influence on the overall failure behaviour of concrete (Akçaoğlu et al., 2005). Furthermore, SEM allows for the investigation of the fracture process zone (FPZ), which refers to the region surrounding a crack tip where significant deformation and damage occur (Hadjab et al., 2007). By utilizing SEM in conjunction with the non-local isotropic damage model, researchers can gain a better understanding of the FPZ in concrete beams, contributing to the development of more accurate fracture models.

In the study conducted by Yu et al. (2022), SEM (Fig. 7) was employed to investigate the fracture behaviour of metakaolin and steel fibre modified concrete with high fluidity. In Fig. 7 (a) MK0-SF0 curing at 7 days; (b) MK15-SF0 curing at 7 days; (c) MK0-SF0 curing at 28 days; (d) MK15-SF0 curing at 28 days. SEM analysis allowed for the examination of micro-facial characteristics, providing valuable insights into the microstructural features of the concrete and the distribution of reinforcing fibres. The high-resolution imaging capability of SEM enabled the observation of crack propagation and damage mechanisms within the concrete matrix.

In addition to fracture analysis, SEM has also been used in conjunction with other techniques, such as acoustic emission, to provide a comprehensive understanding of the fracture behaviour of concrete (Hadjab et al., 2010). By combining SEM imaging with acoustic emission data, researchers can correlate the observed microcracks with the associated acoustic signals, enhancing the characterization and interpretation of the fracture process. However, it is important to acknowledge the limitations of SEM. The preparation of concrete samples for SEM analysis can be challenging, requiring careful sample preparation techniques to ensure accurate results. Additionally, SEM imaging is typically conducted under vacuum conditions, which may affect the moisture content and chemical composition of the concrete surface.

Nevertheless, SEM has significantly contributed to the understanding of the fracture behaviour of concrete. Its high-resolution imaging capability and ability to reveal microstructural details have provided valuable insights into crack initiation, propagation and the influence of various factors on fracture mechanisms. Continued advancements in SEM technology and sample preparation techniques are expected to further enhance its potential for studying fracture phenomena in concrete and contribute to the development of more resilient and durable concrete structures.

4. Modelling Approaches for Fracture Propagation in Concrete

Modelling approaches for fracture propagation in concrete have seen significant progress, utilizing various techniques to simulate and predict crack behaviour. One widely used approach is Continuum Damage Mechanics (CDM), which describes the progressive deterioration of the material through damage variables. The Finite Element Method (FEM) is another commonly employed technique, discretizing the concrete structure into small elements and solving governing equations to analyse crack propagation. Discrete Element Method (DEM) models concrete as an assembly of discrete particles interacting with each other, capturing the granular behaviour of the material. Lattice Discrete Particle Model (LDPM) combines the advantages of DEM and lattice-based models to simulate crack initiation, propagation, and coalescence. Hybrid modelling approaches integrate multiple methods, such as FEM and DEM, to capture different aspects of fracture behaviour. These modelling techniques play a crucial role in enhancing the understanding of fracture.

4.1 Continuum Damage Mechanics (CDM)

Continuum Damage Mechanics (CDM) has gained significant attention in the study of fracture behaviour in concrete due to its ability to capture the progressive damage and failure process of the material. CDM-based models have been utilized in various applications, demonstrating their versatility and effectiveness in analysing different aspects of concrete fracture. One area where CDM has been successfully applied is in fatigue modelling of asphalt concrete (Lee et al., 2000). By incorporating damage evolution laws and fatigue criteria, CDM allows for the prediction of fatigue life and the assessment of the material's durability under cyclic loading conditions. This has significant implications for the design and maintenance of asphalt pavements.

Darabi, et al. (2012) presented a study on the use of continuum damage mechanics (CDM) in studying fracture behaviour in concrete (Fig. 8). They proposed a CDM framework that incorporates micro-damage healing phenomena, aiming to enhance the predictive capabilities of fracture models. The researchers focused on the healing process at the microscale and developed a set of damage evolution equations based on experimental observations. By considering the healing mechanisms, the CDM model could capture the recovery of damaged material properties and the closure of microcracks. The study demonstrated the effectiveness of the CDM approach in modelling fracture behaviour, providing insights into the healing process and its influence on the overall mechanical response of concrete structures.

In the case of fibre-reinforced concrete, CDM has been employed to model the tension behaviour of these composites (Li and Li, 2001). By considering the interaction between the fibres and the matrix, CDM-based models can accurately predict the cracking and failure mechanisms in fibre-reinforced concrete, providing valuable insights for optimising the material's performance in structural applications. To enhance the capabilities of CDM, researchers have integrated it with other numerical methods. For instance, the combination of CDM with the eXtended Finite Element Method (XFEM) allows for the simulation of crack propagation in concrete structures (Roth et al., 2015). By incorporating enriched finite element formulations, XFEM-CDM models can accurately capture crack initiation, growth and branching, enabling detailed analysis of fracture behaviour.

It is important to address the challenges associated with CDM, such as the calibration of material parameters. Obtaining accurate and representative input parameters for damage evolution laws and constitutive models can be complex and requires careful experimental characterization. Additionally, capturing the complex nature of concrete, including heterogeneity and multi-scale behaviour, poses a challenge for CDM-based models. Nonetheless, the development of advanced CDM models has continued to improve their predictive capabilities. For instance, considering the influence of crack direction under quasi-static load has been shown to enhance the accuracy of fracture predictions (Yun et al., 2017). Furthermore, the incorporation of mechanical damage models, such as the Density-Driven

Damage Mechanics (D3-M) model, allows for a more comprehensive assessment of concrete behaviour (Murru et al., 2022).

4.2 Finite Element Method (FEM)

The Finite Element Method (FEM) has emerged as a powerful numerical tool for studying fracture behaviour in concrete structures. This method allows for the simulation of crack propagation and fracture processes, providing valuable insights into the mechanical response and failure mechanisms of concrete. The use of FEM in analysing non-prescribed crack propagation in concrete has been investigated (Alfaiate et al., 1997). By modelling crack growth as a discrete process, FEM can accurately capture the evolution of cracks and their influence on the structural response. Similarly, the modelling of crack closure in FEM simulations has been explored, enhancing the accuracy of stress distribution predictions (Kotsovos & Spiliopoulos, 1998).

To address the challenges associated with mesh-dependent crack propagation simulations, the Extended Finite Element Method (XFEM) has been introduced (Moës & Belytschko, 2002). XFEM allows for the representation of crack surfaces within finite elements, enabling the simulation of complex crack growth patterns and interactions. This approach has shown promise in capturing cohesive crack growth in concrete structures. The development of embedded crack models has further advanced the capabilities of FEM in analysing concrete fracture (Sancho et al., 2007). By embedding cohesive elements along potential crack paths, FEM can simulate crack initiation, propagation and branching. This approach facilitates the investigation of fracture behaviour under different loading conditions and provides valuable insights into crack patterns and energy dissipation. FEM has been applied to study the failure of plain concrete beams under impact loading (Travaš et al., 2009). By incorporating material nonlinearity and dynamic effects, FEM simulations can accurately predict the structural response and failure mechanisms. Similarly, FEM has been employed to analyse crack propagation in prestressed concrete pipes (Alavinasab et al., 2011). The simulations provide crucial information for assessing the structural integrity and safety of such infrastructure.

Hybrid approaches, combining FEM with other numerical methods, have been explored to improve the accuracy and efficiency of fracture modelling in concrete. For instance, the hybrid FEM-scaled boundary finite element method has been utilised to model crack propagation in reinforced concrete (Ooi & Yang, 2011). This approach combines the advantages of both methods, enabling detailed analysis of crack paths and stress distributions. Furthermore, the integration of X-ray CT imaging with FEM has enabled the characterization of asphalt concrete fracture performance (Wang et al., 2018). By incorporating realistic material properties derived from imaging data, FEM simulations can accurately predict crack initiation and propagation, aiding in the optimisation of asphalt concrete mixes.

The use of FEM in studying the fracture of concrete has been demonstrated in the work of Alrayes et al. (2023). Their study focuses on modelling cyclic crack propagation in concrete using the Scaled Boundary Finite Element Method (SBFEM) coupled with the Cumulative Damage-Plasticity (CDP) constitutive law. By incorporating the SBFEM, which is advantageous for crack modelling, and the CDP constitutive law, which accounts for the progressive accumulation of damage, the researchers are able to accurately simulate the behaviour of concrete under cyclic loading conditions. The concept of a cohesive crack model using the SBFEM shown in Fig. 9. This approach provides valuable insights into the fracture process and aids in the understanding and prediction of concrete fracture behaviour. Despite its advantages, the use of FEM in concrete fracture analysis is not without challenges. The accuracy of FEM predictions relies on appropriate material models and the calibration of parameters, which can be complex and require extensive experimental validation. Additionally, the computational cost associated with large-scale FEM simulations may limit their application to specific scenarios.

4.3 Discrete Element Method (DEM)

The Discrete Element Method (DEM) is a computational technique used to study the fracture behaviour of concrete. It provides a numerical approach to analyse the interaction and behaviour of individual particles within a concrete material. By considering the discrete nature of particles and their interactions, DEM allows for the simulation of crack initiation, propagation, and overall fracture processes in concrete. This method offers insights into the mechanical response of concrete under various loading conditions, enabling researchers to understand the fracture mechanisms, stress distribution, and energy dissipation within the material. DEM has proven to be a valuable tool in studying the fracture behaviour of concrete and advancing the knowledge of its structural integrity and performance.

One notable contribution in this area is the work by Liu et al. (2020) (Fig. 10), who proposed a cohesive fracture model based on polyhedral blocks within the DEM framework. By incorporating cohesive elements at the interfaces of the polyhedral blocks, this model enables the simulation of crack initiation, propagation, and coalescence. The study demonstrated the effectiveness of the proposed model in capturing the fracture behaviour of concrete, including crack patterns, energy dissipation and post-failure behaviour. Such advancements in DEM-based fracture modelling contribute to a better understanding of concrete's fracture mechanics and aid in the design and assessment of concrete structures.

The series of studies conducted by Riera et al. (2016), Ren and Sun (2017), Tan et al. (2019), Nitka and Tejchman (2020), Dong et al. (2020), Meza-Lopez et al. (2020), and Xie et al. (2020) collectively contribute to a nuanced understanding of material behaviour, particularly in concrete and asphalt, through the application of DEM. This critical analysis will assess the strengths and limitations of these studies and highlight their impact on advancing the comprehension of structural mechanics and failure processes. One commendable aspect of these studies is their adoption of DEM, a numerical simulation technique that considers the discrete nature of particles and their interactions. This approach provides a detailed and granular perspective on material behaviour, allowing for the exploration of deformation patterns, stress distribution, crack initiation, propagation, and failure mechanisms. The use of DEM facilitates a more realistic representation of the materials under investigation, moving beyond traditional continuum models to capture the intricacies of particle-level interactions.

Riera et al. (2016) and Ren and Sun (2017) specifically focused on concrete and asphalt, respectively, shedding light on their static compression and fracture behaviours. The studies emphasize the importance of considering particle-based characteristics in understanding these materials' responses to external forces. Tan et al. (2019) extended this line of inquiry to recycled aggregate concrete, utilizing DEM to analyse cracking patterns and particle displacement, thereby contributing to sustainable construction practices. Nitka and Tejchman (2020) took a meso-mechanical approach, incorporating interfacial transition zones (ITZs) to capture material heterogeneity in concrete simulations. This novel addition enhances the studies by addressing the complexities of real-world materials, emphasizing the role of ITZs in crack initiation and propagation. Dong et al. (2020) and Meza-Lopez et al. (2020) broadened the scope by investigating the fracture behaviour of cement-treated base materials and asphalt concrete, respectively, under different loading conditions. Their use of DEM allows for a comprehensive analysis of crack initiation, propagation, and overall failure behaviour, providing valuable insights into the materials' structural integrity. Xie et al. (2020) introduced acoustic emission into the DEM framework to study the failure mechanism of porous concrete. This integration adds an additional layer of sophistication by considering not only particle interactions but also acoustic signals, offering a more holistic understanding of the fracture process in porous materials.

However, despite these strengths, some limitations and challenges are notable. Firstly, the accuracy of DEM simulations heavily relies on the calibration of model parameters, and uncertainties may arise in translating simulation results to real-world scenarios. Additionally, the computational demands of DEM can be substantial, limiting the scale and complexity of models that can be practically simulated. The studies utilizing DEM for structural analysis present a commendable advancement in understanding material behaviour at the particle level. The detailed insights into deformation, stress distribution, and failure mechanisms contribute significantly to the field. The incorporation of factors like air voids, recycled aggregates, and acoustic emissions further enriches the analyses. However, researchers should remain cognizant of the challenges associated with DEM, particularly in terms of calibration and computational demands. The collective impact of these studies is evident in their potential to inform not only theoretical understanding but also practical applications in the field of civil engineering and construction.

The use of the DEM in studying the fracture behaviour of concrete has shown promise in providing valuable insights into the mechanical response and failure mechanisms of the material. However, there are several critical considerations that need to be addressed. One limitation of DEM is its computational cost. The particle-based nature of DEM requires modelling a large number of discrete elements, which can be computationally expensive and time-consuming, particularly for large-scale simulations. This restricts the application of DEM to smaller-scale analyses or simplified models, limiting its ability to capture the full complexity of concrete fracture behaviour in real-world scenarios. Another challenge is the representation of material properties in DEM simulations. The accurate characterization of concrete material behaviour, including strength, stiffness, and fracture properties, is crucial for reliable simulations. However, obtaining accurate and representative material properties for each discrete element can be challenging, especially when considering the inherent heterogeneity of concrete. The use of simplified constitutive models and assumptions in DEM simulations may introduce uncertainties and limit the accuracy of the results.

Furthermore, the choice of contact models and parameters in DEM significantly influences the predicted fracture behaviour. The selection of appropriate contact laws and parameters to represent the interactions between discrete elements and their response to cracking and fracture is crucial. However, determining these parameters experimentally can be challenging, leading to uncertainties in the simulation results. The calibration of contact models and parameters remains an ongoing challenge in DEM-based fracture modelling of concrete. Additionally, the validation of DEM results against experimental data is essential to ensure the reliability and accuracy of the simulations. However, obtaining comprehensive and reliable experimental data for validating complex fracture behaviour in concrete can be difficult. The scarcity of experimental data that captures the full range of concrete fracture phenomena limits the ability to fully validate and calibrate DEM models. Despite these challenges, DEM offers unique advantages in capturing the discrete nature of concrete and its fracture behaviour. It allows for the analysis of crack initiation, propagation, and interaction, providing insights into localized deformation and failure mechanisms. DEM can also simulate the influence of various factors such as air voids, aggregates, and porosity on fracture behaviour, providing a detailed understanding of their effects.

4.4 Lattice Discrete Particle Model (LDPM)

The Lattice Discrete Particle Model (LDPM) has emerged as a valuable tool for studying fracture behaviour in concrete. This computational method represents the discrete nature of concrete by modelling it as an assembly of interacting lattice particles. LDPM allows for the simulation of crack initiation, propagation, and coalescence, providing insights into the mechanical response and failure mechanisms of concrete. By capturing the complex interactions between particles and the evolution of cracks, LDPM enables the analysis of fracture processes at various scales, from micro to macro. Its ability to simulate realistic fracture patterns and predict the mechanical behaviour of concrete makes LDPM a promising approach for studying fracture in concrete structures.

The series of studies conducted by Cusatis et al. (2011), Schauffert et al. (2012), Fascetti et al. (2018), and Rezakhani et al. (2017) collectively contribute to the understanding and application of the Lattice Discrete Particle Model (LDPM) in predicting concrete behaviour under various loading conditions. Starting with Cusatis et al. (2011), the emphasis on calibration and validation of the LDPM for concrete failure behaviour is commendable. Accurate determination of model parameters through experimental data is crucial for reliable predictions. The study lays a solid foundation for further development, but it falls short in providing a comprehensive exploration of potential limitations and challenges associated with the LDPM.

Schauffert et al. (2012) built upon the LDPM's capabilities by extending its application to fibre-reinforced concrete under tensile fracture and multiaxial loading conditions. The study successfully demonstrates the LDPM's ability to capture complex behaviours. However, the acknowledgment of limitations, such as the representation of fibre-matrix interaction and parameter calibration challenges, raises concerns about the model's robustness in real-world scenarios. Fascetti et al. (2018) focused on the LDPM's application in modelling concrete under compressive loading. The utilization of a multiscale experimental approach for parameter determination is a noteworthy advancement. While the study provides valuable insights into compressive behaviour, it recognizes ongoing challenges in accurately representing the stress-strain response, leaving room for improvement.

The study by Rezakhani et al. (2017) explored the application of the Lattice Discrete Particle Model (LDPM) in analysing damage and fracture in concrete through adaptive multiscale homogenization. By combining LDPM with strain energy equivalence, the researchers successfully captured the evolving behaviour of concrete at different length scales. The LDPM accurately simulated crack initiation, propagation and localisation, showing good agreement with experimental data and other numerical models. However, limitations such as computational costs and parameter sensitivity were acknowledged. Overall, the study highlights the potential of LDPM with adaptive multiscale homogenisation for understanding concrete fracture behaviour, but further research is needed to refine and validate the model for wider engineering applications. Figure 11 illustrates the crack opening evolution in three Representative Volume Elements (RVEs) associated with three macroscopic Finite Elements (FEs) located within the localization band. The RVE corresponding to macro Element 1 is integrated into the computational process between points (a) and (b) on the force-displacement curve. Damage evolution in this RVE is shown at points (b), (c), (e), and (h). At points (b) and (c), the damage is still distributed throughout the RVE volume. However, at point (e), two inclined localization bands emerge, which subsequently merge into one at point (h), positioned on the softening branch of the force-displacement curve. The RVE assigned to Element 2 is incorporated into the multiscale framework between points (d) and (e). The crack opening evolution in this RVE is also depicted in Fig. 11 at point (e), where the damage is distributed, at point (g) where two inclined localization bands are formed, and at point (h), where one of the localization bands propagates through the RVE. Lastly, the crack opening contour in the RVE assigned to Element 3, which is inserted before point (h), is illustrated at point (h).

The LDPM's capabilities were further extended to simulate concrete thermal spalling by Shen et al. (2020). The multi-physics approach accounted for thermal effects on crack initiation and propagation, offering a comprehensive understanding of thermal spalling phenomena. However, the accuracy of the LDPM in capturing the intricate thermal-mechanical interactions and the influence of material heterogeneity warrants further investigation. Del Prete et al. (2021) explored the use of the LDPM to simulate the viscoelastic behaviour of macro-synthetic fibre-reinforced concrete. This study highlighted the potential of the LDPM in capturing time-dependent material response, although challenges in accurately modelling fibre-matrix interactions and accounting for the influence of temperature variations persist. Zhu et al. (2022) investigated the LDPM's application in simulating cyclic tension-compression behaviour with multi-axial confinement. The study contributed to understanding the behaviour of concrete under cyclic loading, providing insights into crack growth and energy dissipation. However, the model's performance in capturing the complex behaviour of cyclic loading, including fatigue life prediction, requires further validation and refinement.

One of the strengths of the LDPM is its ability to model the mesoscale behaviour of concrete, considering the interactions between discrete particles. This allows for a more detailed representation of the material's response, capturing important phenomena such as crack propagation and material heterogeneity. The LDPM has shown good agreement with experimental results in various scenarios, demonstrating its potential as a predictive tool. However, there are several challenges and limitations associated with the use of the LDPM. Calibration and validation of the model parameters can be complex and time-consuming, requiring extensive experimental data. The selection of appropriate parameters and their accurate representation is crucial for obtaining reliable results. Additionally, the LDPM's computational cost can be significant, particularly for large-scale simulations, limiting its applicability to practical engineering problems. Another limitation is the inherent simplifications and assumptions made in the LDPM. The discrete nature of the model may not fully capture the continuous behaviour of concrete, and the representation of complex features such as aggregate shape and size distribution may require further refinement. The multiscale nature of concrete, with interactions occurring at different length scales, presents a challenge for accurately incorporating all relevant phenomena into the LDPM. Furthermore, the LDPM's predictive capabilities for certain aspects of concrete fracture, such as crack branching and propagation in complex geometries, may still require further development. Improvements in modelling techniques and incorporation of advanced fracture mechanics concepts could enhance the model's accuracy and applicability in real-world scenarios.

4.5 Hybrid Modelling Approaches

Hybrid modelling approaches have emerged as powerful tools to study the fracture behaviour of concrete. These approaches combine the strengths of different numerical methods to capture the complex nature of concrete fracture. Typically, a combination of continuum mechanics and discrete element methods is employed, where the continuum model describes the overall behaviour of the structure while the discrete element model focuses on the localized fracture phenomena. This allows for a more accurate representation of crack initiation, propagation, and interaction with the surrounding material. Hybrid models can also incorporate other techniques such as finite element analysis, cohesive zone modelling, or lattice models to capture specific aspects of concrete fracture. By integrating multiple approaches, hybrid modelling provides a comprehensive understanding of fracture processes in concrete and enables more reliable predictions for engineering applications.

Hybrid modelling approaches have gained significant attention for studying fracture in concrete, as evidenced by several studies in the field. Ooi and Yang (2011) proposed a hybrid finite element-scaled boundary finite element method to model crack propagation in reinforced concrete. Gui et al. (2016) employed a hybrid continuum-discrete element method with a cohesive fracture model to simulate dynamic failure in brittle rocks. Ooi et al. (2017) utilized the scaled boundary finite element method with hybrid polygon-quadtree meshes for crack propagation modelling in concrete. These studies demonstrate the versatility of hybrid approaches in capturing fracture behaviour. Additionally, Taheri et al. (2020) developed an integrated approach for predicting crack width and spacing in flexural fibre-reinforced concrete members with hybrid reinforcement. Balzano et al. (2021) investigated enhanced concrete crack closure using hybrid shape memory polymer tendons, highlighting the potential for hybrid techniques in addressing crack-related issues in concrete structures. Furthermore, Wang et al. (2021) proposed a hybrid potential of mean force approach for simulating fracture in heterogeneous media, showcasing the applicability of hybrid models beyond traditional concrete materials. Sturm et al. (2022) presented a hybrid deterministic-probabilistic approach for characterizing crack widths and spacings in reinforced concrete members.

Althoey et al. (2022) introduced a novel computational approach, leveraging machine learning, for detecting crack widths in self-healing concrete. The researchers integrated traditional computational methods with machine learning algorithms to improve the accuracy and efficiency of crack detection and monitoring. This hybrid methodology harnesses machine learning's capabilities to analyse image data and extract crack features, showcasing its potential in addressing crack-related issues in concrete structures. The SHC-GEP 1 model demonstrated promising results for the testing dataset, with R and R2 values of 0.938 (> 0.8) and 0.880 (> 0.7), respectively, affirming its effectiveness. Figure 12 (b) visually illustrates the disparity in regression line slopes between the training and testing phases. The comparison of experimental and predicted values in Figure 12 (a) highlights a close alignment for the majority of data points. The graphical representation of absolute error in Figure 12 (c) indicates an average absolute percent error below 14.8%, with approximately 80% of the data exhibiting an absolute percent error less than 30%, as depicted in the histogram in Figure 12 (d). This analysis underscores the reliability and robustness of the proposed hybrid modelling techniques in enhancing the assessment and management of crack-related issues in concrete structures.

These studies collectively demonstrate the diverse applications of hybrid modelling approaches in analysing fracture behaviour, crack propagation, crack width prediction and material heterogeneity in concrete. Hybrid models provide a valuable means of combining different numerical techniques, enabling a more comprehensive understanding of concrete fracture and facilitating accurate predictions for practical engineering scenarios. However, further research is needed to address the challenges associated with model calibration, computational efficiency and the integration of different modelling scales to enhance the applicability and reliability of hybrid approaches in concrete fracture analysis.

5. Applications of Fracture Propagation in Concrete

Fracture propagation in concrete has various applications across different fields. In the construction industry, understanding fracture behaviour is crucial for assessing the structural integrity and safety of concrete elements such as beams, columns, and slabs. It helps engineers predict crack propagation and failure modes, enabling them to design more robust structures. In the field of material science, studying fracture propagation in concrete aids in the development of advanced materials with enhanced fracture resistance and durability. Moreover, fracture analysis plays a significant role in evaluating the performance of repair techniques and evaluating the effectiveness of self-healing mechanisms in concrete. Overall, the applications of fracture propagation in concrete contribute to improving structural design, material development and maintenance strategies.

5.1 Structural Health Monitoring (SHM)

Fracture propagation analysis in concrete has important applications in the field of structural health monitoring (SHM). By studying crack propagation patterns, engineers can assess the condition of concrete structures and identify potential areas of concern. This information allows for proactive maintenance and repair strategies, reducing the risk of structural failure. Fracture propagation analysis helps in detecting and monitoring the growth of cracks, which can be indicative of structural deterioration or damage. It aids in determining the severity and extent of cracks, enabling timely interventions and targeted repairs. SHM techniques utilising fracture propagation analysis contribute to the overall safety and longevity of concrete structures by ensuring early detection and appropriate maintenance measures.

The application of fracture propagation analysis in concrete structural health monitoring has emerged as a valuable approach for assessing the condition and performance of concrete structures. One significant aspect is the utilisation of piezoelectric transducers, as highlighted by Saafi and Sayyah (2001). These transducers offer the ability to detect crack initiation and growth by measuring changes in electrical properties. This real-time monitoring capability has the potential to provide early warning signs of structural damage. However, the practical implementation of piezoelectric transducers poses challenges related to their integration into existing concrete structures without compromising their structural integrity. Additionally, the interpretation and analysis of the collected data require sophisticated algorithms and expertise.

Another technique explored in the literature is acoustic emission (AE) monitoring, as discussed by Behnia et al. (2014) and Han et al. (2015). AE monitoring involves capturing and analysing stress waves generated by crack propagation or structural deformation. This approach provides valuable information regarding the location, magnitude, and progression of cracks. However, accurate localisation of crack sources and the differentiation of signals from various sources remain challenging tasks. Factors such as signal attenuation and background noise also limit the effectiveness of AE monitoring.

The application of fracture propagation in concrete structural health monitoring has been explored in the study by Dumoulin et al. (2015) (Fig. 13). Their research focused on monitoring crack propagation in reinforced concrete beams using embedded piezoelectric transducers. By utilizing these transducers, they are able to detect acoustic emissions generated by crack growth, allowing for real-time monitoring of structural integrity. This technique provides valuable information about crack initiation, propagation and potential structural damage, enabling timely interventions and maintenance. The findings presented in the study contribute to the development of non-destructive evaluation techniques in the fracture mechanics of concrete, enhancing the overall safety and durability of concrete structures.

While these studies have demonstrated the potential of fracture propagation analysis for concrete structural health monitoring, there are still several areas that require further research. The integration of sensors into existing concrete structures must be addressed to ensure compatibility with the structural integrity requirements. Additionally, the development of robust algorithms for data analysis and interpretation is crucial for reliable and accurate assessment of structural health. Furthermore, advancements in sensor technology and the exploration of alternative monitoring techniques are necessary to overcome the limitations of current approaches.

In conclusion, fracture propagation analysis has shown promise in concrete structural health monitoring, but there are challenges that need to be addressed for practical implementation. The studies reviewed have provided valuable insights into the use of piezoelectric transducers and AE monitoring for crack detection and evaluation. However, ongoing research efforts are needed to enhance the reliability, accuracy and practicality of these techniques. By addressing these challenges, fracture propagation analysis can play a significant role in improving the safety and durability of concrete structures.

5.2 Design and Optimisation of Concrete Structures

The application of fracture propagation in the design and optimisation of concrete structures plays a crucial role in ensuring their structural integrity and performance. By studying fracture propagation, engineers can analyse the behaviour of cracks under various loading conditions and design structures that can withstand such challenges. Understanding how cracks propagate allows for the development of strategies to minimise their impact and improve the durability of concrete structures. This knowledge can be utilised to optimize reinforcement layouts, select appropriate materials, and design effective crack control measures. By incorporating fracture propagation analysis in the design process, engineers can create more resilient and efficient concrete structures that meet safety standards and provide long-term performance.

In the field of design and optimisation of concrete structures, the application of fracture propagation has been a subject of extensive research and investigation, as evidenced by the literature cited. Stang et al. (1995) conducted a study on stress-crack width relations in fibre-reinforced concrete, aiming to provide practical design guidelines. Their work contributed to the understanding of crack behaviour and its implications for the structural performance of concrete elements. Van Mier and Van Vliet (1999) emphasised the significance of experimentation, numerical simulation, and engineering judgment in comprehending fracture mechanics in concrete and concrete structures. Their research highlighted the need for a multidisciplinary approach to effectively analyse and design concrete elements. Zhang and Li (2004) employed fracture mechanics principles to simulate crack propagation in fibre-reinforced concrete. Their study provided valuable insights into crack behaviour and aided in the development of improved design practices for fibre-reinforced concrete structures. Theiner and Hofstetter (2009) focused on numerical prediction methods for crack propagation and crack widths in concrete structures. Their research contributed to the development of advanced computational techniques for optimising designs and evaluating the structural integrity of concrete elements.

The body of research presented by Kumar and Barai (2011) offers a substantial and comprehensive overview of concrete fracture models and their practical applications. Their work not only delves into the theoretical foundations of fracture analysis in concrete structures but also includes valuable insights from real-world case studies. The inclusion of both theoretical and empirical aspects makes this research particularly impactful for engineers seeking to make informed decisions in the design process. Yang et al.'s (2018) contribution, focused on developing a numerical approach to determine concrete crack width in structures affected by corrosion, addresses a pressing concern in structural engineering. The research acknowledges and tackles the challenges posed by deteriorating concrete due to corrosion, providing valuable information that enhances the understanding of crack propagation in such environments. By doing so, Yang et al. (2018) contribute significantly to the design of corrosion-affected concrete structures.

The stochastic fracture-mechanical parameters proposed by Strauss et al. (2014) for performance-based design of concrete structures represent a noteworthy advancement in the field. By accounting for uncertainties in crack behaviour, their work empowers engineers to create designs that are not only reliable but also robust. This consideration of uncertainties is crucial, especially in real-world scenarios where variations and unexpected factors can significantly impact structural integrity. Mukhtar and El-Tohfa's (2023) review builds upon the existing body of knowledge, providing a comprehensive examination of fracture propagation in concrete. Covering various models, methods, and benchmark tests, their research serves as a valuable synthesis of the current understanding of fracture mechanics in concrete structures. Additionally, by identifying areas for further development and refinement, Mukhtar and El-Tohfa (2023) pave the way for future research and improvements in this critical aspect of structural engineering.

However, it is important to note that while each of these studies contributes significantly to the field, the collective impact of their findings on the practical aspects of structural design and construction may vary. Engineers and practitioners must carefully evaluate and integrate these research findings into their specific contexts, considering factors such as regional variations, material properties, and project requirements. Furthermore, ongoing collaboration and interdisciplinary efforts among researchers, engineers, and industry professionals will be essential to ensuring that these advancements translate effectively into real-world applications and contribute to the continuous improvement of concrete structure design and safety.

Collectively, these studies have significantly contributed to the advancement of design and optimization in concrete structures. By shedding light on fracture propagation, crack behaviour, and numerical prediction techniques, they have enhanced the reliability, durability, and overall performance of concrete structures. Future research in this area can build upon these foundations to further refine design practices and optimize the structural behaviour of concrete elements.

5.3 Failure Analysis and Risk Assessment

The application of fracture propagation in Failure Analysis and risk assessment of concrete structures plays a crucial role in identifying potential failure mechanisms and assessing the associated risks. By understanding how cracks propagate in concrete, engineers can accurately evaluate the structural integrity and predict the failure modes of various components. This information enables the identification of critical areas prone to failure, allowing for targeted inspections, repairs, or reinforcement measures. Furthermore, the analysis of fracture propagation helps in determining the remaining service life of structures, informing decisions on maintenance and rehabilitation strategies.

The case study by Swenson and Ingraffea (1991) on the collapse of the Schoharie Creek Bridge demonstrates the significance of concrete fracture mechanics in investigating failure mechanisms and identifying the factors that contributed to the collapse. By analysing crack propagation patterns and fracture characteristics, researchers can gain insights into the underlying causes of failure and develop strategies to prevent similar incidents in the future. Farnam and Rezaie (2019) focused on the simulation of crack propagation in prestressed concrete sleepers, which are critical components of railway tracks. Their study employed fracture mechanics principles to assess the risk of crack growth and failure in these structural elements. By understanding the behaviour of cracks and their interaction with the prestressing tendons, engineers can evaluate the structural integrity of sleepers and implement maintenance and repair measures to mitigate the risk of failure. De Maio et al. (2019) introduced a refined approach for failure analysis in plain and reinforced concrete structures, emphasizing the importance of fracture mechanics in quasi-brittle materials. By considering cohesive zone modelling and crack propagation simulations, the researchers provided a comprehensive framework for evaluating the performance and failure modes of concrete structures. This approach enables engineers to assess the structural safety and durability of concrete elements and make informed decisions regarding maintenance, repair and design modifications.

Farsi et al. (2020) investigated fracture propagation in fibre-reinforced concrete tunnel linings, which are exposed to various loads and environmental conditions. Their study utilised the FDEM (Finite-Discrete Element Method) to simulate crack growth and evaluate the structural response. By analysing the crack patterns and assessing the influence of fibre reinforcement, the researchers contributed to the understanding of fracture behaviour in these critical infrastructure components. This knowledge can inform risk assessment and help engineers optimize the design and maintenance of tunnel linings to ensure their long-term performance and safety. Brandtner-Hafner (2021) focused on the structural safety evaluation of adhesive bonds, highlighting the importance of fracture analytical approaches. By considering fracture mechanics principles and adhesive bond strength, the study provided insights into the behaviour and failure modes of adhesive joints. This knowledge aids in assessing the reliability and durability of adhesive-bonded structures, such as composite materials and bonded connections, contributing to risk assessment and ensuring the integrity of these structural components.

Bui et al. (2021) investigated the failure analysis of masonry wall panels subjected to in-plane and out-of-plane loading using the discrete element method. Their study highlighted the role of fracture analysis in understanding the failure mechanisms and assessing the risk of structural collapse in masonry structures. By considering crack propagation and failure patterns, the researchers provided valuable information for structural assessment, maintenance, and retrofitting of masonry walls. Wang et al. (2022) conducted a numerical investigation on crack propagation in concrete gravity dams under static and dynamic loads, considering the effect of in-crack reservoir pressure. Their study contributed to the understanding of crack propagation processes and the evaluation of dam safety. By analysing the crack behaviour and assessing the stability of concrete dams, engineers can identify potential failure modes and develop risk mitigation strategies.

In summary, the application of fracture propagation analysis in Failure Analysis and risk assessment of concrete structures enables engineers to gain insights into failure mechanisms, evaluate structural integrity, and develop preventive measures. These studies highlight the importance of understanding crack propagation patterns, fracture behaviour and the interaction of cracks with various factors such as prestressing, reinforcement, adhesive bonds and environmental conditions. By incorporating fracture mechanics principles into failure analysis and risk assessment processes, engineers can enhance the safety and reliability of concrete structures, contributing to the sustainability of infrastructure systems.

5.4 Repair and Rehabilitation Strategies

The application of fracture propagation analysis in repair and rehabilitation strategies for concrete structures, particularly in the context of mitigating reflection cracking, is a critical area of study. Dhakal et al. (2016) synthesised various mitigation strategies for reflection cracking in rehabilitated pavements. By analysing the behaviour of cracks and their propagation, the researchers proposed strategies such as interlayer systems, geosynthetics, and modified binders to minimize the occurrence and progression of reflection cracks. This study highlighted the importance of fracture mechanics in understanding the mechanisms of reflection cracking and developing effective repair techniques.

Wei et al. (2014) focused on evaluating the performance of different materials used for concrete pavement joint repair to reduce reflective cracking in asphalt concrete overlays. The study assessed the behaviour of cracks and their propagation at the joint interfaces and evaluated the effectiveness of repair materials in preventing crack propagation. By considering fracture mechanics principles, the researchers provided insights into the durability and long-term performance of repair strategies and their ability to mitigate reflection cracking. The application of fracture propagation analysis in repair and rehabilitation strategies allows engineers to assess the behaviour of cracks in concrete structures and develop techniques that minimize crack propagation and reduce the occurrence of reflection cracking. By understanding the mechanisms of crack formation and propagation, engineers can select appropriate repair materials and techniques to ensure the longevity and functionality of rehabilitated pavements and concrete structures.

However, it is essential to acknowledge that the effectiveness of fracture propagation-based repair and rehabilitation strategies may vary depending on factors such as environmental conditions, traffic loads, and the specific characteristics of the structure being repaired. The application of fracture mechanics principles in repair and rehabilitation should be accompanied by thorough site-specific assessments and considerations of the local conditions and requirements. Additionally, the long-term performance and durability of the repair strategies should be monitored and evaluated to ensure their effectiveness over the service life of the structure.

In summary, the application of fracture propagation analysis in repair and rehabilitation strategies for concrete structures offers valuable insights into the behaviour of cracks and their propagation. These studies provide guidance for selecting appropriate materials and techniques to mitigate reflection cracking and enhance the performance and durability of rehabilitated pavements. However, further research and field validation are necessary to optimise and fine-tune these strategies for specific conditions and to ensure their long-term effectiveness in repair and rehabilitation applications.

6. Research Opportunities and Areas of Improvement

Research opportunities and areas of improvement in fracture propagation in concrete include improved understanding of microstructural effects, sustainable and eco-friendly concrete solutions, dynamic fracture propagation, multi-scale modelling and experimental validation, durability aspects, advanced sensing and monitoring techniques, integration of artificial intelligence and machine learning and field studies and case studies. By investigating these areas, researchers can enhance the understanding of fracture behaviour in concrete, develop advanced materials and structures, improve predictive models and contribute to the safety, durability, and sustainability of concrete infrastructure.

1. Improved Understanding of Microstructural Effects:
   Investigating the influence of concrete's microstructure on fracture propagation is an important research opportunity. This includes studying the role of aggregate characteristics, cementitious matrix properties and interfacial bonding on crack initiation, propagation path, and energy dissipation. Understanding these microstructural effects can lead to the development of advanced concrete materials with enhanced fracture resistance.

2. Sustainable and Eco-Friendly Concrete Solutions:
   There is a growing demand for sustainable and eco-friendly construction materials. Research in this area can focus on exploring fracture propagation in concrete made with alternative binders, recycled aggregates and supplementary cementitious materials. Investigating the fracture behaviour of these sustainable concretes will contribute to their wider adoption in the construction industry.

3. Dynamic Fracture Propagation: While fracture propagation in concrete under static loading conditions has been extensively studied, there is a need for research on dynamic fracture propagation. Investigating how cracks propagate in concrete under dynamic loading, such as impact and blast loads, is crucial for assessing the structural integrity and safety of concrete structures subject to dynamic events.

4. Multi-Scale Modelling and Experimental Validation:
   Integrating multi-scale modelling approaches with experimental validation can significantly enhance the understanding of fracture propagation in concrete. Research can focus on developing advanced multi-scale models that capture the behaviour of concrete from the micro to macro scale. These models can be validated and calibrated using experimental data obtained from state-of-the-art imaging and sensing techniques.

5. Durability Aspects: Fracture propagation in concrete is strongly influenced by environmental factors and long-term exposure to aggressive conditions. Research can investigate the effects of moisture, temperature variations, chemical attacks and freeze-thaw cycles on fracture initiation and propagation. Understanding the durability aspects of fracture propagation will aid in the development of more resilient and durable concrete structures.
6. Advanced Sensing and Monitoring Techniques:
   Research can focus on the development and implementation of advanced sensing and monitoring techniques for real-time detection and characterization of fracture propagation in concrete structures. This includes the use of wireless sensor networks, embedded sensors and remote monitoring systems. Such techniques can provide valuable data for structural health monitoring, early warning systems and maintenance strategies.

7. Integration of Artificial Intelligence and Machine Learning: The integration of artificial intelligence and machine learning techniques can revolutionise the study of fracture propagation in concrete. Research can explore the use of AI-based algorithms for fracture prediction, optimisation of fracture-resistant designs and automated interpretation of experimental data. This can expedite the analysis process and provide valuable insights into fracture behaviour.

8. Field Studies and Case Studies: Conducting field studies and case studies on real-world concrete structures experiencing fracture propagation can provide valuable insights into the behaviour of concrete under practical conditions. This research opportunity involves monitoring and analysing existing structures, identifying failure mechanisms and proposing retrofitting and repair strategies to mitigate fracture-related issues.

By focusing on these research opportunities and areas of improvement, the understanding of fracture propagation can be advanced in concrete and contribute to the development of safer, more durable and sustainable concrete structures.

7. Concluding Remarks

The study of fracture propagation in concrete is of significant importance for the understanding and management of concrete structures. This review has provided a comprehensive overview of the fundamentals, experimental techniques, modelling approaches and applications related to fracture propagation in concrete. The review highlighted the complex nature of fracture propagation, including the factors influencing crack initiation, propagation mechanisms and different types of fractures in concrete. Understanding these fundamental aspects is crucial for predicting and controlling the behaviour of concrete structures under various loading conditions.

Various experimental techniques, both non-destructive and destructive, were discussed in the review. These techniques play a vital role in detecting, monitoring, and characterising fractures in concrete. The advancements in imaging techniques, such as acoustic emission, ultrasonic testing, and digital image correlation, have enabled researchers to capture and analyse the fracture behaviour at different stages. Modelling approaches, including continuum damage mechanics, finite element method, discrete element method and lattice discrete particle model, were explored in the review. These modelling techniques offer valuable insights into the mechanical behaviour of concrete and provide a platform for predicting fracture propagation and structural response. The review also highlighted the practical applications of studying fracture propagation in concrete. Structural health monitoring, design optimisation, failure analysis and rehabilitation strategies are among the key areas where the understanding of fracture propagation is crucial. By applying this knowledge, engineers can enhance the safety, durability and performance of concrete structures.

In conclusion, this review paper emphasises the importance of fracture propagation in concrete and provides a foundation for further research and advancements in the field. By exploring the identified research opportunities and areas of improvement, the understanding of fracture propagation in concrete can continue to be enhanced, leading to more resilient and sustainable concrete structures in the future.

References:

- Abdalla, H. M., & Karihaloo, B. L. (2003). Determination of size-independent specific fracture energy of concrete from three-point bend and wedge splitting tests. Magazine of concrete research, 55(2), 133-141.
- Aggelis, D.G. (2011). Classification of cracking mode in concrete by acoustic emission parameters. Mechanics Research Communications, 38(3), pp.153-157. • Aggelis, D.G., Soulioti, D.V., Sapouridis, N., Barkoula, N.M., Paipetis, A.S., & Matikas, T.E. (2011). Acoustic emission characterization of the fracture process in fibre reinforced concrete. Construction and Building Materials, 25(11), 4126-4131.
- Aïssoun, B.M., Hwang, S.D., & Khayat, K.H. (2016). Influence of aggregate characteristics on workability of superworkable concrete. Materials and Structures, 49, 597-609.
- Aïtcin, P.C. (2003). The durability characteristics of high performance concrete: a review. Cement and Concrete Composites, 25(4-5), 409-420.
- Akçaoğlu, T. (2017). Determining aggregate size & shape effect on concrete microcracking under compression by means of a degree of reversibility method. Construction and Building Materials, 143, 376-386.
- Akçaoğlu, T., Tokyay, M., & Çelik, T. (2005). Assessing the ITZ microcracking via scanning electron microscope and its effect on the failure behavior of concrete. Cement and Concrete Research, 35(2), 358-363.
- Alam, S.Y., Saliba, J., & Loukili, A. (2014). Fracture examination in concrete through combined digital image correlation and acoustic emission techniques. Construction and Building Materials, 69, 232-242.
- Aldahdooh, M.A.A., & Bunnori, N.M. (2013). Crack classification in reinforced concrete beams with varying thicknesses by mean of acoustic emission signal features. Construction and Building Materials, 45, pp.282-288.
- Alfaiate, J., Pires, E.B., & Martins, J.A.C. (1997). A finite element analysis of non-prescribed crack propagation in concrete. Computers & Structures, 63(1), 17-26.
- Al-Harthy, A.S., Stewart, M.G., and Mullard, J. (2011). Concrete cover cracking caused by steel reinforcement corrosion. Magazine of Concrete Research, 63(9), 655-667.
- Alavinasab, A., Padewski, E. III, Higgins, M., Holley, M., Jha, R., & Ahmadi, G. (2011). Crack propagation in prestressed concrete noncylinder pipe using finite element method. In Pipelines 2011: A Sound Conduit for Sharing Solutions (pp. 55-64).
- Alfaiate, J., Pires, E.B., & Martins, J.A.C. (1997). A finite element analysis of non-prescribed crack propagation in concrete. Computers & Structures, 63(1), 17-26.
- Alrayes, O., Könke, C., Ooi, E.T., & Hamdia, K.M. (2023). Modeling Cyclic Crack Propagation in Concrete Using the Scaled Boundary Finite Element Method Coupled with the Cumulative Damage-Plasticity Constitutive Law. Materials, 16(2), 863.
- Alshaikh, I.M., Bakar, B.A., Alwesabi, E.A., Zeyad, A.M., & Magbool, H.M. (2021). Finite element analysis and experimental validation of progressive collapse of reinforced rubberized concrete frame. Structures, 33, 2361-2373.
- Althoey, F., Amin, M.N., Khan, K., Usman, M.M., Khan, M.A., Javed, M.F., Sabri, M.M., Alrowais, R. and Maglad, A.M., 2022. Machine learning based computational approach for crack width detection of self-healing concrete. Case Studies in Construction Materials, 17, p.e01610.
- Balzano, B., Sweeney, J., Thompson, G., Tuinea-Bobe, C.L., & Jefferson, A. (2021). Enhanced concrete crack closure with hybrid shape memory polymer tendons. Engineering Structures, 226, p. 111330.
- Banjara, N. K., Sasmal, S., & Srinivas, V. (2019). Investigations on acoustic emission parameters during damage progression in shear deficient and GFRP strengthened reinforced concrete components. Measurement, 137, 501-514.
- Basheer, L., Basheer, P.A.M., & Long, A.E. (2005). Influence of coarse aggregate on the permeation, durability, and the microstructure characteristics of ordinary Portland cement concrete. Construction and Building Materials, 19(9), 682-690.

- Bencardino, F., Rizzuti, L., Spadea, G., & Swamy, R.N. (2010). Experimental evaluation of fiber reinforced concrete fracture properties. Composites Part B: Engineering, 41(1), 17-24.
- Bisschop, J., & Van Mier, J.G.M. (2002). How to study drying shrinkage microcracking in cement-based materials using optical and scanning electron microscopy?. Cement and Concrete Research, 32(2), 279-287.
- Bhosale, A.B., & Prakash, S.S. (2020). Crack propagation analysis of synthetic vs. steel vs. hybrid fiber-reinforced concrete beams using digital image correlation technique. International Journal of Concrete Structures and Materials, 14(1), 1-19.
- Borosnyói, A., & Balázs, G.L. (2005). Models for flexural cracking in concrete: the state of the art. Structural Concrete, 6(2), 53-62.
- Brandtner-Hafner, M. (2021). Structural safety evaluation of adhesive bonds: A fracture analytical approach. Engineering Failure Analysis, 123, p. 105289.
- Bui, T.T., Limam, A., & Sarhosis, V. (2021). Failure analysis of masonry wall panels subjected to in-plane and out-of-plane loading using the discrete element method. European Journal of Environmental and Civil Engineering, 25(5), 876-892.
- Bazant, Z.P., & Xu, K. (1991). Size effect in fatigue fracture of concrete. ACI Materials Journal, 88(4), 390-399.
- Behnia, A., Chai, H.K., & Shiotani, T. (2014). Advanced structural health monitoring of concrete structures with the aid of acoustic emission. Construction and Building Materials, 65, 282-302.
- Cachim, P.B. (2009). Mechanical properties of brick aggregate concrete. Construction and Building Materials, 23(3), 1292-1297.
- César B., J., Dersch, M.S., Edwards, J.R., & Andrawes, B.O. (2017). Flexural behavior of concrete crossties under different support conditions. Journal of Transportation Engineering, Part A: Systems, 143(12), 04017064.
- Chen, C., Chen, X., & Fan, X. (2020). Experimental investigation of concrete fracture behavior with different loading rates based on acoustic emission. Construction and Building Materials, 237, 117472.
- Chen, L., Lu, Q., & Qian, Z. (2014). Crack initiation and propagation in epoxy asphalt concrete in the three-point bending test. Road Materials and Pavement Design, 15(3), 507-520.
- Chen, W.F., & Yuan, R.L. (1980). Tensile strength of concrete: Double-punch test. Journal of the Structural Division, 106(8), 1673-1693.
- Cifuentes, H., Fernandez-Canteli, A., Holušová, T., Lozano, M., Medina, F., & Seitl, S. (2017). Modified disk-shaped compact tension test for measuring concrete fracture properties. International Journal of Concrete Structures and Materials, 11(2), 215-228.
- Corr, D., Accardi, M., Graham-Brady, L., & Shah, S. (2007). Digital image correlation analysis of interfacial debonding properties and fracture behavior in concrete. Engineering Fracture Mechanics, 74(1-2), 109-121.
- Cusatis, G., Bažant, Z.P., & Cedolin, L. (2006). Confinement-shear lattice CSL model for fracture propagation in concrete. Computer methods in applied mechanics and engineering, 195(52), 7154-7171.
- Cusatis, G., Pelessone, D., & Mencarelli, A. (2011). Lattice discrete particle model (LDPM) for failure behavior of concrete. I: Theory. Cement and Concrete Composites, 33(9), 881-890.
- Dao, V.T., Morris, P.H., & Dux, P.F. (2014). Crack propagation in concrete at very early ages. Magazine of Concrete Research, 66(13), 643-651.
- Darabi, M.K., Abu Al-Rub, R.K., & Little, D.N. (2012). A continuum damage mechanics framework for modeling micro-damage healing. International Journal of Solids and Structures, 49(3–4), 492-513.

- Dastgerdi, A.S., Peterman, R.J., Riding, K., & Beck, B.T. (2019). Effect of concrete mixture components, proportioning, and compressive strength on fracture parameters. Construction and Building Materials, 206, 179-192.
- Dehestani, A., Hosseini, M., & Beydokhti, A.T. (2020). Effect of wetting-drying cycles on mode I and mode II fracture toughness of cement mortar and concrete. Theoretical and Applied Fracture Mechanics, 106, 102448.
- Del Prete, C., Boumakis, I., Wan-Wendner, R., Vorel, J., Buratti, N., & Mazzotti, C. (2021). A lattice discrete particle model to simulate the viscoelastic behaviour of macro–synthetic fibre reinforced concrete. Construction and Building Materials, 295, 123630.
- Demirboga, R., & Kan, A. (2012). Thermal conductivity and shrinkage properties of modified waste polystyrene aggregate concretes. Construction and Building Materials, 35, 730-734.
- De Maio, U., Greco, F., Leonetti, L., Luciano, R., Nevone Blasi, P., & Vantadori, S. (2019). A refined diffuse cohesive approach for the failure analysis in quasibrittle materials—part II: Application to plain and reinforced concrete structures. Fatigue & Fracture of Engineering Materials & Structures, 42(12), pp.2764-2781.
- De Wolski, S.C., Bolander, J.E., & Landis, E.N. (2014). An in-situ X-ray microtomography study of split cylinder fracture in cement-based materials. Experimental Mechanics, 54, 1227-1235.
- Dhakal, N., Elseifi, M.A., & Zhang, Z. (2016). Mitigation strategies for reflection cracking in rehabilitated pavements–A synthesis. International Journal of Pavement Research and Technology, 9(3), 228-239.
- Dondeti, S., & Tippur, H.V. (2022). Crack initiation and slow growth in soda-lime glass from a self-healed crack. Theoretical and Applied Fracture Mechanics, 119, 103341.
- Dong, Q., Zheng, D., Zhao, X., Chen, X., & Chen, Y. (2020). Mesoscale numerical simulation of fracture of cement treated base material during semi-circular bending test with discrete element model, Construction and Building Materials, 261, p.119981.
- Dong, W., Wu, Z., Zhou, X., Wang, N., & Kastiukas, G. (2017). An experimental study on crack propagation at rock-concrete interface using digital image correlation technique. Engineering Fracture Mechanics, 171, pp.50-63.
- Dostaler, I., Gagnon, S., & De Blois, J. (2006). An experimental and analytical investigation of the effects of curing on the shrinkage behavior of concrete. Cement and Concrete Research, 36(7), 1354-1366.
- Dumoulin, C., Karaiskos, G., & Deraemaeker, A. (2015). Monitoring of crack propagation in reinforced concrete beams using embedded piezoelectric transducers. In Acoustic Emission and Related Non-Destructive Evaluation Techniques in the Fracture Mechanics of Concrete (pp. 161-175). Woodhead Publishing.
- Dutler, N., Nejati, M., Valley, B., Amann, F., & Molinari, G. (2018). On the link between fracture toughness, tensile strength, and fracture process zone in anisotropic rocks. Engineering Fracture Mechanics, 201, 56-79.
- Dzik, E.J., & Lajtai, E.Z. (1996). Primary fracture propagation from circular cavities loaded in compression. International Journal of Fracture, 79, 49-64.
- du Plessis, A., & Boshoff, W.P. (2019). A review of X-ray computed tomography of concrete and asphalt construction materials. Construction and Building Materials, 199, 637-651.
- Emborg, M. and Bernander, S. (1994). Assessment of risk of thermal cracking in hardening concrete. Journal of Structural Engineering, 120(10), 2893-2912.
- Erzar, B. and Forquin, P. (2010). An experimental method to determine the tensile strength of concrete at high rates of strain. Experimental Mechanics, 50(7), 941-955.
- Farnam, S.M. & Rezaie, F. (2019). Simulation of crack propagation in prestressed concrete sleepers by fracture mechanics. Engineering Failure Analysis, 96, 109-117.

- Farnam, Y., Geiker, M.R., Bentz, D., & Weiss, J. (2015). Acoustic emission waveform characterization of crack origin and mode in fractured and ASR damaged concrete. Cement and Concrete Composites, 60, 135-145.
- Farsi, A., Bedi, A., Latham, J.P. & Bowers, K. (2020). Simulation of fracture propagation in fibre-reinforced concrete using FDEM: an application to tunnel linings. Computational Particle Mechanics, 7, 961-974.
- Fascetti, A., Bolander, J. E., & Nisticó, N. (2018). Lattice discrete particle modeling of concrete under compressive loading: Multiscale experimental approach for parameter determination. Journal of Engineering Mechanics, 144(8), 04018058.
- Fayyad, T. M., & Lees, J. M. (2014). Application of digital image correlation to reinforced concrete fracture. Procedia Materials Science, 3, 1585-1590.
- Fayyad, T. M., & Lees, J. M. (2017). Experimental investigation of crack propagation and crack branching in lightly reinforced concrete beams using digital image correlation. Engineering Fracture Mechanics, 182, 487-505.
- Garcia, V.J., Marquez, C.O., Zuniga-Suarez, A.R., Zuniga-Torres, B.C., & Villalta-Granda, L.J. (2017). Brazilian test of concrete specimens subjected to different loading geometries: Review and new insights. International Journal of Concrete Structures and Materials, 11, 343-363.
- Gao, P., Chen, Y., Huang, H., Qian, Z., Schlangen, E., Wei, J., & Yu, Q. (2020). Investigation of drying-induced non-uniform deformation, stress, and micro-crack propagation in concrete. Cement and Concrete Composites, 114, 103786.
- Garoz, D., Gilabert, F.A. & Van Paepegem, W. (2015). Stress concentrations and bonding strength in encapsulation-based self-healing materials. Materials & Design, 67, 28-41.
- Ghalehnovi, M., Karimipour, A., & de Brito, J. (2019). Influence of steel fibers on the flexural performance of reinforced concrete beams with lap-spliced bars. Construction and Building Materials, 229, 116853.
- Giaccio, G., Zerbino, R., Ponce, J.M., & Batic, O.R. (2008). Mechanical behavior of concretes damaged by alkali-silica reaction. Cement and Concrete Research, 38(7), 993-1004.
- Gilabert, F.A., Garoz, D., and Van Paepegem, W. (2015). Stress concentrations and bonding strength in encapsulation-based self-healing materials. Materials & Design, 67, 28-41.
- Glasser, F.P. (1991). Chemistry of the alkali-aggregate reaction. In The alkali-silica reaction in concrete (pp. 30-53). CRC Press.
- Golewski, G.L. (2019). Measurement of fracture mechanics parameters of concrete containing fly ash thanks to use of Digital Image Correlation (DIC) method. Measurement, 135, 96-105.
- Grosse, C., Reinhardt, H., & Dahm, T. (1997). Localization and classification of fracture types in concrete with quantitative acoustic emission measurement techniques. NDT & E International, 30(4), 223-230.
- Grosse, C.U., & Finck, F. (2006). Quantitative evaluation of fracture processes in concrete using signal-based acoustic emission techniques. Cement and Concrete Composites, 28(4), 330-336.
- Gui, Y.L., Bui, H.H., Kodikara, J., Zhang, Q.B., Zhao, J. and Rabczuk, T., (2016). Modelling the dynamic failure of brittle rocks using a hybrid continuum-discrete element method with a mixed-mode cohesive fracture model. International Journal of Impact Engineering, 87, pp.146-155.
- Guo, H., Ooi, E.T., Saputra, A.A., Yang, Z., Natarajan, S., Ooi, E.H., & Song, C. (2019). A quadtree-polygon-based scaled boundary finite element method for image-based mesoscale fracture modelling in concrete. Engineering Fracture Mechanics, 211, 420-441.

- Guo, T., Liu, K., Ma, S., Yang, J., Li, X., Zhou, K., and Qiu, T. (2022). Dynamic fracture behavior and fracture toughness analysis of rock-concrete bi-material with interface crack at different impact angles. Construction and Building Materials, 356, 129286.
- Guo, Z.K., Kobayashi, A.S., & Hawkins, N.M. (1995). Dynamic mixed mode fracture of concrete. International Journal of Solids and Structures, 32(17-18), 2591-2607.
- Hadjab, H., Chabaat, M., & Thimus, J.F. (2007). Use of scanning electron microscope and the non-local isotropic damage model to investigate the fracture process zone in notched concrete beams. Experimental Mechanics, 47, 473-484.
- Hadjab, H., Thimus, J.F., & Chabaat, M. (2010). Comparative study of acoustic emission and scanning electron microscope to evaluate the fracture process zone in concrete beams. Journal of Materials in Civil Engineering, 22(11), 1156-1163.
- Han, Q., Xu, J., Carpinteri, A., & Lacidogna, G. (2015). Localization of acoustic emission sources in structural health monitoring of masonry bridge. Structural Control and Health Monitoring, 22(2), 314-329.
- He, Y., Zhang, X., Hooton, R.D., and Zhang, X. (2017). Effects of interface roughness and interface adhesion on new-to-old concrete bonding. Construction and Building Materials, 151, 582-590.
- Hong, S., Liu, P., Zhang, J., Kuang, C., Dong, B., Luo, Q., & Liu, W. (2020). Interior fracture analysis of rubber-cement composites based on X-ray computed tomography and digital volume correlation. Construction and Building Materials, 259, 119833.
- Huang, Y., Guan, Y., Wang, L., Zhou, J., Ge, Z., & Hou, Y. (2018). Characterization of mortar fracture based on three-point bending test and XFEM. International Journal of Pavement Research and Technology, 11(4), 339-344.
- Huang, Y., He, X., Wang, Q., & Xiao, J. (2019). Deformation field and crack analyses of concrete using digital image correlation method. Frontiers of Structural and Civil Engineering, 13, 1183-1199.
- Huang, Y., Yan, D., Yang, Z., & Liu, G. (2016). 2D and 3D homogenization and fracture analysis of concrete based on in-situ X-ray Computed Tomography images and Monte Carlo simulations. Engineering Fracture Mechanics, 163, 37-54.
- Huang, Y., Yang, Z., Ren, W., Liu, G., & Zhang, C. (2015). 3D meso-scale fracture modeling and validation of concrete based on in-situ X-ray Computed Tomography images using damage plasticity model. International Journal of Solids and Structures, 67, 340-352.
- Hu, S., Lu, J., & Xiao, F. (2013). Evaluation of concrete fracture procedure based on acoustic emission parameters. Construction and Building Materials, 47, 1249-1256.
- Iyer, S., Sinha, S.K., Pedrick, M.K., and Tittmann, B.R. (2012). Evaluation of ultrasonic inspection and imaging systems for concrete pipes. Automation in Construction, 22, 149-164.
- Jia, M., Wu, Z., Yu, R.C., & Zhang, X. (2023). Modeling of Mixed Mode I–II Fatigue Fracture of Concrete Based on Paris Law. Journal of Materials in Civil Engineering, 35(5), 04023078.
- Jirásek, M., & Grassl, P. (2008). Evaluation of directional mesh bias in concrete fracture simulations using continuum damage models. Engineering Fracture Mechanics, 75(8), 1921-1943.
- Jin, G.L., Zhang, Z.X., & Huang, X.M. (2021). Fatigue cracking analysis of asphalt concrete based on coupled XFEM-continuum damage mechanics method. Journal of Materials in Civil Engineering, 33(1), 04020425.
- Jones, R.M. (2018). Mechanics of composite materials. CRC press.
- Kang, S.T., Lee, Y., Park, Y.D., and Kim, J.K. (2010). Tensile fracture properties of an Ultra High Performance Fiber Reinforced Concrete (UHPFRC) with steel fiber. Composite Structures, 92(1), 61-71.

- Kaur, N.P., Shah, J.K., Majhi, S., & Mukherjee, A. (2019). Healing and simultaneous ultrasonic monitoring of cracks in concrete. Materials Today Communications, 18, 87-99.
- Ke, Y., Beaucour, A.L., Ortola, S., Dumontet, H., & Cabrillac, R. (2009). Influence of volume fraction and characteristics of lightweight aggregates on the mechanical properties of concrete. Construction and Building Materials, 23(8), 2821-2828.
- Keerthana, K., & Kishen, J.C. (2021). Micromechanical Effects of Loading Frequency on Fatigue Fracture in Concrete. Journal of Engineering Mechanics, 147(12), 04021111.
- Khosravani, M.R., Silani, M., & Weinberg, K. (2018). Fracture studies of ultra-high-performance concrete using dynamic Brazilian tests. Theoretical and Applied Fracture Mechanics, 93, 302-310.
- Kim, H., Kim, G., Gucunski, N., Nam, J., & Jeon, J. (2015). Assessment of flexural toughness and impact resistance of bundle-type polyamide fiber-reinforced concrete. Composites Part B: Engineering, 78, 431-446.
- Kim, H., Wagoner, M.P., & Buttlar, W.G. (2009). Numerical fracture analysis on the specimen size dependency of asphalt concrete using a cohesive softening model. Construction and Building Materials, 23(5), 2112-2120.
- Kim, K.H., Jeon, S.E., Kim, J.K., & Yang, S. (2003). An experimental study on thermal conductivity of concrete. Cement and Concrete Research, 33(3), 363-371.
- Kotsovos, M.D., & Spiliopoulos, K.V. (1998). Modelling of crack closure for finite-element analysis of structural concrete. Computers & Structures, 69(3), 383-398.
- Konsta-Gdoutos, M.S., Metaxa, Z.S., & Shah, S.P. (2010). Multi-scale mechanical and fracture characteristics and early-age strain capacity of high-performance carbon nanotube/cement nanocomposites. Cement and Concrete Composites, 32(2), 110-115.
- Kong, W., Wei, Y., Wang, S., Chen, J., & Wang, Y. (2020). Research progress on cement-based materials by X-ray computed tomography. International Journal of Pavement Research and Technology, 13, 366-375.
- Kumar, S., & Barai, S.V. (2009). Determining double-K fracture parameters of concrete for compact tension and wedge splitting tests using weight function. Engineering Fracture Mechanics, 76(7), 935-948.
- Kumar, S., & Barai, S.V. (2011). Concrete fracture models and applications (pp. 1-8). Berlin: Springer.
- Kumar, S., & Barai, S.V. (2012). Size-effect of fracture parameters for crack propagation in concrete: a comparative study. Computers & Concrete, 9(1), 1-19.
- Laefer, D.F., Ambrozevitch-Cooper, N., Huynh, M.P., Midgette, J., Ceribasi, S., & Wortman, J. (2010). Expansive fracture agent behaviour for concrete cracking. Magazine of Concrete Research, 62(6), 443-452.
- Landis, E.N., & Baillon, L. (2002). Experiments to relate acoustic emission energy to fracture energy of concrete. Journal of Engineering Mechanics, 128(6), 698-702.
- Larosche, C.J. (2009). Types and causes of cracking in concrete structures. In Failure, distress and repair of concrete structures (pp. 57-83). Woodhead Publishing.
- Lawrence, C.D. (1990). Sulphate attack on concrete. Magazine of Concrete Research, 42(153), 249-264.
- Lee, H.J., Daniel, J.S., & Kim, Y.R. (2000). Continuum damage mechanics-based fatigue model of asphalt concrete. Journal of materials in Civil Engineering, 12(2), 105-112.
- Li, F., & Li, Z. (2001). Continuum damage mechanics based modeling of fiber reinforced concrete in tension. International journal of solids and structures, 38(5), 777-793.

- Li, J., Wu, Z., Shi, C., Yuan, Q., & Zhang, Z. (2020). Durability of ultra-high performance concrete–A review. Construction and Building Materials, 255, 119296.
- Li, N., Zhao, Y., Xing, Y., & He, X. (2023). Localized Damage Analysis of Cement Mortar Using X-ray Computed Tomography In Situ Compressive Loading and Digital Volume Correlation. Applied Sciences, 13(6), 3842.
- Li, T., Xiao, J., Zhang, Y., & Chen, B. (2019). Fracture behavior of recycled aggregate concrete under three-point bending. Cement and Concrete Composites, 104, 103353.
- Li, V.C., & Maalej, M. (1996). Toughening in cement-based composites. Part I: Cement, mortar, and concrete. Cement and Concrete Composites, 18(4), pp.223-237.
- Li, V.C., & Matsumoto, T. (1998). Fatigue crack growth analysis of fiber reinforced concrete with effect of interfacial bond degradation. Cement and Concrete Composites, 20(5), 339-351.
- Lin, Y., and Karadelis, J.N. (2019). Interfacial fracture toughness of composite concrete beams. Construction and Building Materials, 213, 413-423.
- Liu, G.-Y., Xu, W.-J., Govender, N., & Wilke, D. N. (2020). A cohesive fracture model for discrete element method based on polyhedral blocks. Powder Technology, 359, 190-204.
- López, C.M., Carol, I., & Aguado, A. (2008). Meso-structural study of concrete fracture using interface elements. II: compression, biaxial and Brazilian test. Materials and structures, 41, 601-620.
- Lorenzoni, R., Lima, V.N., Figueiredo, T.C.S., Hering, M., Paciornik, S., Curbach, M., Mechtcherine, V., & de Andrade Silva, F. (2022). Macro and meso analysis of cement-based materials subjected to triaxial and uniaxial loading using X-ray microtomography and digital volume correlation. Construction and Building Materials, 323, 126558.
- Mac, M.J., Yio, M.H.N., Wong, H.S., and Buenfeld, N.R. (2021). Analysis of autogenous shrinkage-induced microcracks in concrete from 3D images. Cement and Concrete Research, 144, 106416.
- Mak, M.W.T., & Lees, J.M. (2023). Arch action in reinforced concrete subjected to shear. Engineering Structures, 274, 115096.
- Maruyama, I. and Lura, P. (2019). Properties of early-age concrete relevant to cracking in massive concrete. Cement and Concrete Research, 123, 105770.
- Medina, C., Zhu, W., Howind, T., de Rojas, M.I.S., & Frías, M. (2014). Influence of mixed recycled aggregate on the physical-mechanical properties of recycled concrete. Journal of Cleaner Production, 68, 216-225.
- Meza-Lopez, J., Noreña, N., Meza, C., & Romanel, C. (2020). Modeling of asphalt concrete fracture tests with the discrete-element method. Journal of Materials in Civil Engineering, 32(8), 04020228.
- Mindess, S., & Bentur, A. (1985). A preliminary study of the fracture of concrete beams under impact loading, using high-speed photography. Cement and Concrete Research, 15(3), 474-484.
- Moës, N., & Belytschko, T. (2002). Extended finite element method for cohesive crack growth. Engineering fracture mechanics, 69(7), 813-833.
- Monney, F., Fernández Ruiz, M., & Muttoni, A. (2023). Influence of amount of shear reinforcement and its post-yield response on the shear resistance of reinforced concrete members. Structural Concrete, 24(1), 1002-1034.
- Mukhtar, F., & El-Tohfa, A. (2023). A review on fracture propagation in concrete: Models, methods, and benchmark tests. Engineering Fracture Mechanics, p.109100.
- Murru, P.T., Torrence, C., Grasley, Z., Rajagopal, K.R., Alagappan, P., & Garboczi, E. (2022). Density-driven damage mechanics (D3-M) model for concrete I: mechanical damage. International Journal of Pavement Engineering, 23(4), 1161-1174.
- Nemati, K.M. (1997). Fracture analysis of concrete using scanning electron microscopy. Scanning, 19(6), 426-430.

- Nejati, H.R., Nazerigivi, A., Imani, M., & Karrech, A. (2020). Monitoring of fracture propagation in brittle materials using acoustic emission techniques-A review. Comput. Concr, 25, pp.15-27.
- Nguyen, D.L., Kim, D.J., Ryu, G.S., & Koh, K.T. (2013). Size effect on flexural behavior of ultra-high-performance hybrid fiber-reinforced concrete. Composites Part B: Engineering, 45(1), 1104-1116.
- Nitka, M. & Tejchman, J. (2020) Meso-mechanical modelling of damage in concrete using discrete element method with porous ITZs of defined width around aggregates, Engineering Fracture Mechanics, 231, 107029.
- Nor, N.M., Ibrahim, A., Bunnori, N.M., & Saman, H.M. (2013). Acoustic emission signal for fatigue crack classification on reinforced concrete beam. Construction and Building Materials, 49, pp.583-590.
- Nor, N.M. (2018). Structural health monitoring through acoustic emission. In Eco-Efficient Repair and Rehabilitation of Concrete Infrastructures (pp. 123-146). Woodhead Publishing.
- Olesen, J.F. (2001). Fictitious crack propagation in fiber-reinforced concrete beams. Journal of Engineering Mechanics, 127(3), 272-280.
- Ollivier, J.P. (1985). A non-destructive procedure to observe the microcracks of concrete by scanning electron microscopy. Cement and Concrete Research, 15(6), 1055-1060.
- Ohno, K., Uji, K., Ueno, A., & Ohtsu, M. (2014). Fracture process zone in notched concrete beam under three-point bending by acoustic emission. Construction and building materials, 67, pp.139-145.
- Ohno, K., & Ohtsu, M. (2010). Crack classification in concrete based on acoustic emission. Construction and Building Materials, 24(12), pp.2339-2346.
- Ooi, E.T., & Yang, Z.J. (2011). Modelling crack propagation in reinforced concrete using a hybrid finite element-scaled boundary finite element method. Engineering Fracture Mechanics, 78(2), 252-273.
- Ooi, E.T., Natarajan, S., Song, C. and Ooi, E.H., 2017. Crack propagation modelling in concrete using the scaled boundary finite element method with hybrid polygon–quadtree meshes. International Journal of Fracture, 203, pp.135-157.
- Ortiz, M. and Popov, E.P. (1982). Plain concrete as a composite material. Mechanics of materials, 1(2), pp.139-150.
- Ožbolt, J., Sharma, A., & Reinhardt, H.W. (2011). Dynamic fracture of concrete–compact tension specimen. International journal of solids and structures, 48(10), pp.1534-1543.
- Ožbolt, J., Bošnjak, J., & Sola, E. (2013). Dynamic fracture of concrete compact tension specimen: Experimental and numerical study. International Journal of Solids and Structures, 50(25-26), pp.4270-4278.
- Padilla, A., Genedy, M., Knight, E.E., Rougier, E., Stormont, J., & Reda Taha, M.M. (2022). Monitoring Postpeak Crack Propagation in Concrete in the Brazilian Tension Test. Journal of Materials in Civil Engineering, 34(6), p.04022110.
- Park, T., Ahmed, B., & Voyiadjis, G.Z. (2022). A review of continuum damage and plasticity in concrete: Part I-Theoretical framework. International Journal of Damage Mechanics, 31(6), 901-954.
- Peng, Z., Shi, C., Shi, Z., Lu, B., Wan, S., Zhang, Z., Chang, J., & Zhang, T. (2020). Alkali-aggregate reaction in recycled aggregate concrete. Journal of cleaner production, 255, 120238.
- Pilehvar, S., Szczotok, A.M., Rodríguez, J.F., Valentini, L., Lanzón, M., Pamies, R., & Kjøniksen, A.L. (2019). Effect of freeze-thaw cycles on the mechanical behavior of geopolymer concrete and Portland cement concrete containing micro-encapsulated phase change materials. Construction and Building Materials, 200, 94-103.

- Prassianakis, I.N. & Giokas, P. (2003). Mechanical properties of old concrete using destructive and ultrasonic non-destructive testing methods. Magazine of Concrete Research, 55(2), 171-176.
- Prassianakis, I.N. & Prassianakis, N.I. (2004). Ultrasonic testing of non-metallic materials: concrete and marble. Theoretical and Applied Fracture Mechanics, 42(2), 191-198.
- Prokopski, G. & Langier, B. (2000). Effect of water/cement ratio and silica fume addition on the fracture toughness and morphology of fractured surfaces of gravel concretes. Cement and Concrete Research, 30(9), 1427-1433.
- Qiao, P., & Xu, Y. (2004). Evaluation of fracture energy of composite-concrete bonded interfaces using three-point bend tests. Journal of Composites for Construction, 8(4), 352-359.
- Rezakhani, R., Zhou, X., & Cusatis, G. (2017). Adaptive multiscale homogenization of the lattice discrete particle model for the analysis of damage and fracture in concrete. International Journal of Solids and Structures, 125, 50-67.
- Rhardane, A., Sleiman, S.A.H., Alam, S.Y., & Grondin, F. (2021). A quantitative assessment of the parameters involved in the freeze-thaw damage of cement-based materials through numerical modelling. Construction and Building Materials, 272, 121838.
- Riera, J.D., Miguel, L.F.F. & Iturrioz, I. (2016). Evaluation of the discrete element method (DEM) and of the experimental evidence on concrete behaviour under static 3D compression, Fatigue & Fracture of Engineering Materials & Structures, 39(11), 1366-1378.
- Ringot, E., & Bascoul, A. (2001). About the analysis of microcracking in concrete. Cement and concrete composites, 23(2-3), 261-266.
- Ríos, J.D., Leiva, C., Ariza, M.P., Seitl, S., & Cifuentes, H. (2019). Analysis of the tensile fracture properties of ultra-high-strength fiber-reinforced concrete with different types of steel fibers by X-ray tomography. Materials & Design, 165, 107582.
- Robert, J.L., Gervais, J.P., & Bruhat, D. (1990). The use of acoustic emission in fracture mechanics applied to concrete. Engineering Fracture Mechanics, 35(4-5), 751-763.
- Rocco, C., Guinea, G.V., Planas, J., & Elices, M. (1999). Size effect and boundary conditions in the Brazilian test: Experimental verification. Materials and Structures, 32, 210-217.
- Rocha, J., & Figueiras, J. (2007). Assessment of nonlinear fracture models for concrete in the context of an XFEM formulation. Engineering Fracture Mechanics, 74(6), 974-996.
- Rocha, J., &Figueiras, J. (2009). A new family of crack propagation laws for concrete and other quasi-brittle materials. International Journal for Numerical Methods in Engineering, 79(6), 733-762.
- Rocha, J., Galvín, A.P., & Figueiras, J. (2005). Two crack propagation models for concrete using the extended finite element method. Engineering Fracture Mechanics, 72(7), 1055-1083.
- Rocha, J., Galvín, A.P., & Figueiras, J. (2005). An XFEM formulation for concrete fracture. Engineering Fracture Mechanics, 72(9), 1285-1311.
- Rocha, J., Figueiras, J., & Figueiredo, S. (2008). Analysis of crack propagation paths in concrete by means of the extended finite element method. Engineering Fracture Mechanics, 75(9), 2694-2712.
- Rocha, J., Galvín, A.P., & Figueiras, J. (2006). A numerical approach for modelling localized fracture in concrete. Computational Mechanics, 37(4), 332-344.
- Rocha, J., Figueiras, J., & Rots, J.G. (2010). Fracture processes in concrete under various stress states. Engineering Fracture Mechanics, 77(13), 2600-2618.

- Rocha, J., & Figueiras, J. (2012). Crack initiation and propagation in quasi-brittle materials under mixed-mode conditions: A theoretical and computational study. International Journal for Numerical Methods in Engineering, 90(5), 652-682.
- Rocha, J., & Figueiras, J. (2012). Numerical simulation of dynamic crack propagation using the extended finite element method. International Journal for Numerical Methods in Engineering, 89(4), 472-496.
- Rocha, J., & Figueiras, J. (2014). Numerical modelling of dynamic fracture in quasi-brittle materials using the XFEM and the virtual internal bond model. Computational Materials Science, 94, 207-219.
- Rocha, J., & Figueiras, J. (2015). Numerical simulation of fracture in quasi-brittle materials with an extended finite element formulation. Computational Mechanics, 55(6), 1197-1215.
- Rocha, J., & Figueiras, J. (2017). Analysis of dynamic crack propagation in quasi-brittle materials with a cohesive crack model. Computational Mechanics, 60(1), 57-78.
- Rocha, J., Figueiras, J., & Rots, J.G. (2017). Analysis of fracture processes in concrete using the X-FEM: Influence of stress and displacement gradients. Engineering Fracture Mechanics, 173, 106-131.
- Rocha, J., Figueiras, J., & Rots, J.G. (2018). Multiscale analysis of fracture in quasi-brittle materials with an application to concrete. Engineering Fracture Mechanics, 191, 202-232.
- Rocha, J., & Figueiras, J. (2020). Numerical modeling of fracture in quasi-brittle materials: A review. Archives of Computational Methods in Engineering, 27(1), 45-97.
- Rossi, P., Boulay, C., Tailhan, J.L., Martin, E., & Desnoyers, D. (2014). Macrocrack propagation in concrete specimens under sustained loading: Study of the physical mechanisms. Cement and Concrete Research, 63, pp.98-104.
- Rossi, P., Robert, J.L., Gervais, J.P., & Bruhat, D. (1990). The use of acoustic emission in fracture mechanics applied to concrete. Engineering Fracture Mechanics, 35(4-5), 751-763.
- Rother, P., Sobczyk, K., Kropp, J., & Meschke, G. (2019). A 3D coupled thermal–hydrological–mechanical approach for the analysis of pore pressure build-up and fracture in concrete. Engineering Fracture Mechanics, 215, 84-104.
- Roth, S.N., Léger, P., & Soulaïmani, A. (2015). A combined XFEM–damage mechanics approach for concrete crack propagation. Computer Methods in Applied Mechanics and Engineering, 283, 923-955.
- Rucka, M., Wojtczak, E., Knak, M., & Kurpińska, M. (2021). Characterization of fracture process in polyolefin fibre-reinforced concrete using ultrasonic waves and digital image correlation. Construction and Building Materials, 280, 122522.
- Różański, M., Kozicki, J., & Tejchman, J. (2021). Microcracking and fragmentation of concrete under dynamic compressive loading. Cement and Concrete Research, 148, 106439.
- Saafi, M., & Sayyah, T. (2001). Health monitoring of concrete structures strengthened with advanced composite materials using piezoelectric transducers. Composites Part B: Engineering, 32(4), 333-342.
- Saleem, M., & Gutierrez, H. (2021). Using artificial neural network and non-destructive test for crack detection in concrete surrounding the embedded steel reinforcement. Structural Concrete, 22(5), pp.2849-2867.
- Sagar, R.V., & Prasad, B.R. (2011). An experimental study on acoustic emission energy as a quantitative measure of size-independent specific fracture energy of concrete beams. Construction and Building Materials, 25(5), 2349-2357.
- Sagar, R.V., Prasad, B.R., & Kumar, S.S. (2012). An experimental study on cracking evolution in concrete and cement mortar by the b-value analysis of acoustic emission technique. Cement and Concrete Research, 42(8), 1094-1104.

- Sancho, J.M., Planas, J., Cendón, D.A., Reyes, E., & Gálvez, J.C. (2007). An embedded crack model for finite element analysis of concrete fracture. Engineering Fracture Mechanics, 74(1-2), 75-86.
- Sanal, I. (2020). Effect of shear span-to-depth ratio on mechanical performance and cracking behavior of high strength steel fiber-reinforced concrete beams without conventional reinforcement. Mechanics of Advanced Materials and Structures, 27(21), 1849-1864
- Santiago, S.D., & Hilsdorf, H.K. (1973). Fracture mechanisms of concrete under compressive loads. Cement and Concrete Research, 3(4), pp.363-388.
- Sarkar, S., Chakraborty, S., & Nayak, S. (2023). Identification of optimum reinforcement detailing using tuned CDP parameters in RC beam under drop-weight impact. Engineering Failure Analysis, 146, 107116.
- Sarfarazi, V., & Haeri, H. (2016). A review of experimental and numerical investigations about crack propagation. Comput. Concrete, 18(2), pp.235-266.
- Schauffert, E. A., Cusatis, G., Pelessone, D., O'Daniel, J. L., & Baylot, J. T. (2012). Lattice discrete particle model for fiber-reinforced concrete. II: Tensile fracture and multiaxial loading behavior. Journal of Engineering Mechanics, 138(7), 834-841.
- Shah, S.P., Swartz, S.E., & Ouyang, C. (1995). Fracture mechanics of concrete: applications of fracture mechanics to concrete, rock and other quasi-brittle materials. John Wiley & Sons.
- Shah, S.G., & Kishen, J.C. (2010). Fracture behavior of concrete–concrete interface using acoustic emission technique. Engineering Fracture Mechanics, 77(6), 908-924.
- Shah, A.A., & Ribakov, Y. (2010). Effectiveness of nonlinear ultrasonic and acoustic emission evaluation of concrete with distributed damages. Materials & Design, 31(8), 3777-3784.
- Shah, S. G., & Chandra Kishen, J. M. (2011). Fracture properties of concrete–concrete interfaces using digital image correlation. Experimental mechanics, 51, 303-313.
- Shah, S.P., Popovics, J.S., Subramaniam, K.V., & Aldea, C.M. (2000). New directions in concrete health monitoring technology. Journal of Engineering Mechanics, 126(7), 754-760
- Shaikh, F.U.A. (2018). Effect of cracking on corrosion of steel in concrete. International Journal of Concrete Structures and Materials, 12, 1-12.
- Shen, L., Li, W., Zhou, X., Feng, J., Di Luzio, G., Ren, Q., & Cusatis, G. (2020). Multiphysics lattice discrete particle model for the simulation of concrete thermal spalling. Cement and Concrete Composites, 106, 103457.
- Shin, H.Y., Thamburaja, P., Srinivasa, A., & Reddy, J.N. (2022). On simulating impact fracture in high-strength concrete using GraFEA. Extreme Mechanics Letters, 52, 101618.
- Shiotani, T., Aggelis, D.G., & Makishima, O. (2009). Global monitoring of large concrete structures using acoustic emission and ultrasonic techniques: case study. Journal of Bridge Engineering, 14(3), 188-192.
- Skarżyński, Ł., & Tejchman, J. (2016). Experimental investigations of fracture process in concrete by means of X-ray micro-computed tomography. Strain, 52(1), 26-45.
- Słowik, M. (2019). The analysis of failure in concrete and reinforced concrete beams with different reinforcement ratio. Archive of Applied Mechanics, 89, 885-895.
- Sokhansefat, G., Ley, M.T., Cook, M.D., Alturki, R., & Moradian, M. (2019). Investigation of concrete workability through characterization of aggregate gradation in hardened concrete using X-ray computed tomography. Cement and Concrete Composites, 98, 150-161.
- Stang, H., Li, V.C., & Krenchel, H. (1995). Design and structural applications of stress-crack width relations in fibre reinforced concrete. Materials and Structures, 28, 210-219.

- Stauffer, J.D., Woodward, C.B., & White, K.R. (2005). Nonlinear ultrasonic testing with resonant and pulse velocity parameters for early damage in concrete. ACI Materials Journal, 102(2), 118.
- Strauss, A., Zimmermann, T., Lehký, D., Novák, D., & Keršner, Z. (2014). Stochastic fracture-mechanical parameters for the performance-based design of concrete structures. Structural Concrete, 15(3), 380-394.
- Struble, L., Skalny, J., & Mindess, S. (1980). A review of the cement-aggregate bond. Cement and Concrete Research, 10(2), 277-286.
- Sturm, A.B., Visintin, P. & Bennett, B., 2022. A hybrid deterministic-probabilistic approach for the characteristic crack widths and crack spacings in reinforced concrete tension and flexural members. Engineering Structures, 256, p.114071.
- Subramaniam, K.V., Popovics, J.S., & Shah, S.P. (2002). Fatigue fracture of concrete subjected to biaxial stresses in the tensile C-T Region. Journal of Engineering Mechanics, 128(6), 668-676.
- Sun, W., & Wu, S. (2021). A study of crack initiation and source mechanism in the Brazilian test based on moment tensor. Engineering Fracture Mechanics, 246, 107622.
- Sun, X., Gao, Z., Cao, P., Zhou, C., Ling, Y., Wang, X., Zhao, Y., & Diao, M. (2019). Fracture performance and numerical simulation of basalt fiber concrete using three-point bending test on notched beam. Construction and Building Materials, 225, 788-800.
- Suzuki, T., Shiotani, T., & Ohtsu, M. (2017). Evaluation of cracking damage in freeze-thawed concrete using acoustic emission and X-ray CT image. Construction and Building Materials, 136, 619-626.
- Swenson, D.V. & Ingraffea, A.R. (1991). The collapse of the Schoharie Creek Bridge: a case study in concrete fracture mechanics. International Journal of Fracture, 51, pp.73-92.
- Taheri, M., Barros, J.A. and Salehian, H., 2020. Integrated approach for the prediction of crack width and spacing in flexural FRC members with hybrid reinforcement. Engineering Structures, 209, p.110208.
- Tan, X., Li, W., Zhao, M. and Tam, V.W. (2019) 'Numerical discrete-element method investigation on failure process of recycled aggregate concrete', Journal of Materials in Civil Engineering, 31(1), p.04018353.
- Tang, Y., Chen, H., & Xiao, J. (2022). Size effects on the characteristics of the fracture process zone of plain concrete under three-point bending. Construction and Building Materials, 315, 125725.
- Tayeh, B.A., Hamada, H.M., Almeshal, I., & Bakar, B.A. (2022). Durability and mechanical properties of cement concrete comprising pozzolanic materials with alkali-activated binder: A comprehensive review. Case Studies in Construction Materials, e01429.
- Theiner, Y., & Hofstetter, G. (2009). Numerical prediction of crack propagation and crack widths in concrete structures. Engineering Structures, 31(8), 1832-1840.
- Travaš, V., Ožbolt, J., & Kožar, I. (2009). Failure of plain concrete beam at impact load: 3D finite element analysis. International journal of fracture, 160, 31-41.
- Trawiński, W., Tejchman, J., & Bobiński, J. (2018). A three-dimensional meso-scale modelling of concrete fracture, based on cohesive elements and X-ray µCT images. Engineering fracture mechanics, 189, 27-50.
- Van Mier, J.G.M., and Van Vliet, M.R.A. (2003). Influence of microstructure of concrete on size/scale effects in tensile fracture. Engineering Fracture Mechanics, 70(16), 2281-2306.
- Van Mier, J.G.M., & Van Vliet, M.R.A. (1999). Experimentation, numerical simulation and the role of engineering judgement in the fracture mechanics of concrete and concrete structures. Construction and Building Materials, 13(1-2), 3-14.

- Wang, T.T. (2010). Characterizing crack patterns on tunnel linings associated with shear deformation induced by instability of neighboring slopes. Engineering geology, 115(1-2), 80-95.
- Wang, H., Wang, C., You, Z., Yang, X., & Huang, Z. (2018). Characterising the asphalt concrete fracture performance from X-ray CT Imaging and finite element modelling. International Journal of Pavement Engineering, 19(3), 307-318.
- Wang, X., Botshekan, M., Ulm, F.J., Tootkaboni, M. and Louhghalam, A., 2021. A hybrid potential of mean force approach for simulation of fracture in heterogeneous media. Computer Methods in Applied Mechanics and Engineering, 386, p.114084.
- Wang, Y.J., Wu, Z.M., Qu, F.M., and Zhang, W. (2022). Numerical investigation on crack propagation process of concrete gravity dams under static and dynamic loads with in-crack reservoir pressure. Theoretical and Applied Fracture Mechanics, 117, p.103221.
- Wang, Z., Xie, J., Jiang, X.F., & Yan, J.B. (2021). Behaviours of reinforced concrete-filled GFRP tube stub columns under low-temperature axial compression. Construction and Building Materials, 312, 125429.
- Wei, Y., Gao, X., & Zhang, Q. (2014). Evaluating performance of concrete pavement joint repair using different materials to reduce reflective cracking in asphalt concrete overlay. Road Materials and Pavement Design, 15(4), 966-976.
- Whittier, S., Olyniec, J., and McGlohn, R. (2004). Minimizing temperature differentials in mass concrete. Concrete International, 26(12), 42-45.
- Wittmann, F.H. (1985). Influence of time on crack formation and failure of concrete. In Application of Fracture Mechanics to Cementitious Composites (pp. 593-615).
- Wittmann, F.H., Mihashi, H., & Nomura, N. (1990). Size effect on fracture energy of concrete. Engineering Fracture Mechanics, 35(1-3), 107-115.
- Wu, Z., Rong, H., Zheng, J., Xu, F., & Dong, W. (2011). An experimental investigation on the FPZ properties in concrete using digital image correlation technique. Engineering Fracture Mechanics, 78(17), 2978-2990.
- Xie, C., Yuan, L., Zhao, M., & Jia, Y. (2020). Study on failure mechanism of porous concrete based on acoustic emission and discrete element method. Construction and Building Materials, 235, 117409.
- Xie, Z. L., Zhou, H. F., Lu, L. J., & Chen, Z. A. (2017). An investigation into the fracture behavior of geopolymer concrete with digital image correlation technique. Construction and Building Materials, 155, 371-380.
- Xu, S., & Reinhardt, H. W. (1999). Determination of double-K criterion for crack propagation in quasi-brittle fracture, Part III: Compact tension specimens and wedge splitting specimens. International Journal of Fracture, 98, 179-193.
- Yang, J.M., Min, K.H., Shin, H.O., & Yoon, Y.S. (2012). Effect of steel and synthetic fibers on flexural behavior of high-strength concrete beams reinforced with FRP bars. Composites Part B: Engineering, 43(3), 1077-1086.
- Yang, R., Xu, Y., Chen, P., & Wang, J. (2020). Experimental study on dynamic mechanics and energy evolution of rubber concrete under cyclic impact loading and dynamic splitting tension. Construction and Building Materials, 262, 120071.
- Yang, S.T., Li, K.F., & Li, C.Q. (2018). Numerical determination of concrete crack width for corrosion-affected concrete structures. Computers & Structures, 207, 75-82.
- Yang, Z., Ren, W., Sharma, R., McDonald, S., Mostafavi, M., Vertyagina, Y., & Marrow, T.J. (2017). In-situ X-ray computed tomography characterisation of 3D fracture evolution and image-based numerical homogenisation of concrete. Cement and Concrete Composites, 75, 74-83.
- Yang, Z., Weiss, W.J., & Olek, J. (2006). Water transport in concrete damaged by tensile loading and freeze-thaw cycling. Journal of materials in civil engineering, 18(3), 424-434.

- Yin, Y., Qiao, Y., & Hu, S. (2020). Determining concrete fracture parameters using three-point bending beams with various specimen spans. Theoretical and Applied Fracture Mechanics, 107, p.102465.
- Yun, K., Wang, Z., Ronald, S., & Pak, Y. (2017). An advanced continuum damage mechanics model for predicting the crack progress process based on the consideration of the influence of crack direction under quasi-static load. International Journal of Mechanical Sciences, 130, 487-496.
- Yu, Z., Zhang, T., & Deng, Y. (2022). The micro-facial characteristics and mechanical behavior of metakaolin and steel fibers modified concrete at high fluidity. Case Studies in Construction Materials, 16, e01019.
- Zhang, C., Shi, F., Cao, P., & Liu, K. (2022). The fracture toughness analysis of basalt fiber reinforced asphalt concrete with prenotched three-point bending beam test. Case Studies in Construction Materials, 16, e01079.
- Zhang, J., & Li, V.C. (2004). Simulation of crack propagation in fiber-reinforced concrete by fracture mechanics. Cement and Concrete Research, 34(2), 333-339.
- Zhang, K., Wang, C., Zhao, Y., & Bi, J. (2023). Experimental study on cracking behavior of concrete containing hole defects. Journal of Building Engineering, 65, 105806.
- Zhang, R., Castel, A., & François, R. (2009). The corrosion pattern of reinforcement and its influence on serviceability of reinforced concrete members in chloride environment. Cement and Concrete Research, 39(11), 1077-1086.
- Zhao, J., Cai, J.G., Zhao, X.B., and Li, H.B. (2006). Experimental study of ultrasonic wave attenuation across parallel fractures. Geomechanics and Geoengineering: An International Journal, 1(2), 87-103
- Zhu, Y., Zhang, Y., Hussein, H.H., & Cai, S. (2020). Flexural study on UHPC–steel composite beams with joints under negative bending moment. Journal of Bridge Engineering, 25(10), 04020084.
- Zhu, Z., Pathirage, M., Wang, W., Troemner, M., & Cusatis, G. (2022). Lattice discrete particle modeling of concrete under cyclic tension–compression with multi-axial confinement. Construction and Building Materials, 352, 128985.

Figure captions:

Fig. 1-Acoustic emission due to crack growth in a solid material under stress

Fig. 2- Investigation on AE parameters during Damage Progression in SD and SSD reinforced concrete components (Banjara et al. 2019)

Fig. 3- Ultrasound testing for assessing crack propagation and healing in concrete structures (Kaur et al. 2019)

Fig. 4- Comparison of DIC results with experimental results from clip gauge readings for CTOD- (a) HB75 beam (b) PO75 beam (Bhosale and Prakash 2020)

Fig. 5- X-ray CT image of the no fibre (a) micro-fibre (b) macro-fibre (c) and micro-and macro-fibres (d) mixes (Rios et al. 2019)

Fig. 6- DVC computing 3D image and distribution of principal strain under different stress stages (Li et al. 2023)

Fig. 7- SEM images of paste-aggregate bonding interface (Yu et al. 2022)

Fig. 8- Schematic representation (a) damaged partially healed cylinder in tension (b) nominal (c) healing and (d) effective (Darabi et al. 2012)

Fig. 9- The concept of a cohesive crack model using the scaled boundary finite element method (Alrayes et al. 2023)

Fig. 10- The relation between stress and strain and breakage ratio (Liu et al. 2020)

Fig. 11- Image evolution in RVEs assigned to three macro finite elements within the localization band (Rezakhani et al. 2017)

Fig. 12- Statistical assessment of SHC-GEP-1 model (Althoey et al. 2022)

Fig. 13- Monitoring of crack propagation in reinforced concrete beams using embedded piezoelectric transducers (Dumoulin et al. 2015)