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Research Article

Comparative evaluation of reinforced concrete culverts under static loading: Impact of reinforcement deterioration through experimental and FEM approaches

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Abstract

This study examines the impact of reinforcement deterioration on the structural performance of reinforced concrete (RC) culverts under static loading conditions, with a focus on damage patterns and load-displacement responses. Deterioration significantly impacts the longevity and safety of concrete structures, especially in adverse environmental conditions. An experimental investigation was conducted on eight RC culverts of circular and rectangular shapes with variations in reinforcing bar type and reinforcement continuity. Finite Element Modelling (FEM) using ABAQUS was also employed to simulate the structural response of jointed and disjointed culverts under static loads. The findings reveal a significant reduction in load-bearing capacity and ductility in disjointed reinforced culverts, with FEM results having an average correlation of 82% with experimental results. For culverts reinforced with jointed steel bars, the highest-performing was the rectangular jointed steel (RJS) culvert, which had an initial crack load of 15kN in the experimental test, compared to 12kN predicted by the FEM analysis. The lowest-performing jointed culvert was the circular jointed steel (CJS), with experimental and FEM results of 7kN and 9kN, respectively. Among the disjointed reinforced culverts, the circular disjointed mesh (CDM) exhibited the lowest performance, with initial crack loads of 7kN experimentally and 8kN from FEM simulation. The highest-performing disjointed reinforced culvert was the circular disjointed steel (CDS), achieving 11kN in both experimental and FEM results. These findings underscore the detrimental effect of reinforcement deterioration and highlight the importance of proactive inspection and reinforcement retrofitting to ensure structural integrity and extend the lifespan of culverts.

1. Introduction

During Engineering practice involves a significant amount of conflict resolution, not in terms of argument, but in placing multiple structures in the same location. Numerous challenges arise when getting these structures to go over, under, and around each other. These include bridges, culverts, and aqueducts, which are ubiquitous in the construction environment and serve the sole purpose of dealing with conflicts between roadways and streams, canals, and ditches. Culverts are crucial in preventing water overflow, which is dangerous to lives and property. Well-designed culverts have also been proven to be a potential support to wildlife movement [1]. Culverts allow streams, canals, and ditches to pass freely, ensuring that embankments do not impede natural water flow.

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Moreover, culverts counteract floodwaters on either side of the embankment, thereby lowering flood levels on one side of the road, reducing water pressure, and mitigating flood risks [2]. While factors like serviceability and expected lifespan are important for maintaining highways, the failure of a culvert can result in the loss of a roadway. Therefore, it is crucial to consider culvert failure as a sudden and unforeseen risk to public safety [3]. Once culverts are backfilled with soil, they become difficult to monitor; therefore, it is pertinent to ensure they are properly constructed to guarantee long-term serviceability and safety. Reinforced concrete (RC) is widely valued in structural engineering due to its strength, durability, and versatility. Its ability to withstand a wide range of environmental conditions, such as varying temperatures, moisture levels, and even chemical exposure, makes it an ideal material for many structures, such as buildings, culverts, and bridges. Reinforcement, typically using steel bars, helps concrete resist tensile stresses, enhancing its load-bearing capacity and durability. However, despite its robustness, reinforced concrete can be prone to issues like bond deterioration, corrosion, and cracking over time, particularly in aggressive environments. These vulnerabilities can significantly degrade structural performance and service life if not properly addressed. Numerous instances of RC culvert failure have led to flooding, infrastructure damage, traffic disruption, injuries, and even loss of life [4].

The structural performance of reinforced concrete culverts (RCCs) has come under increasing scrutiny, with numerous studies aimed at understanding factors influencing their stability and longevity. Researchers have explored the vulnerabilities of both precast and cast-in-place RCCs, examining issues such as material degradation, load-bearing capacity, and environmental impacts [5]. These investigations are crucial for improving design standards and preventing premature failures, ensuring RCC structures can withstand long-term stresses and harsh conditions. Through site inspections and destructive testing, it was discovered that underground RC box culverts which were around 30 years old were experiencing gradual and excessive deformation and the culverts' top slabs were deflecting 10 times more than their estimated design value and were accompanied by out-of-plane shear cracks which were due to a combination of subsidence of the backfill soil and the combined creep and shrinkage of concrete after cracking [6].

In recent years, attention has shifted towards evaluating the durability and structural behaviour of RCCs using both experimental and numerical methods. Jawdhari et al. (7) used two-dimensional finite element models (FEM) to analyze bridge-sized RC arch culverts subjected to live loads under large fills. It was found that the controlling actions are bending moments at the crown and haunch for fills above 2.43 m, and live load effects become negligible for fills beyond 3.05 m. Aoki et al. [8] also investigated the impact of chlorine-induced deterioration on the structural performance of underground reinforced concrete structures, specifically box and pipe culverts, when subjected to external forces such as ground subsidence and fault movement. They used experimental and analytical methods, specifically finite element analysis. The study found that chloride-induced degradation can compromise the durability of underground structures, posing challenges in preserving their internal space. The failure mode was influenced by the location of steel corrosion, which altered the direction of the shear zone in the surrounding soil.

In another study, Babawat et al. (9) examined an aged RC bridge structure nearing the end of its design life due to deterioration from heavy traffic loads and inadequate maintenance. A detailed investigation revealed that the reinforcement had significantly deteriorated, reducing the load-carrying capacity of the structure. Utilizing ABAQUS with FEM, the researchers found that Ultra-High-Performance Fiber-Reinforced Concrete (UHPFRC) outperformed conventional materials under realistic traffic loads, while CFRP (Carbon Fiber Reinforced Polymer) retrofitting provided the greatest flexural resistance at higher loads. To further explore the effects of corrosion, Almassri et al. [9] developed a three-dimensional FEM model in ABAQUS to analyze the failure mode of a repaired, corroded RC beam. Their simulation results showed strong correlation with experimental data, accurately predicting both the load-bearing capacity and the reduction in ultimate deflection caused by corrosion.

Waqas et al. [10] conducted a study utilizing the finite element method (FEM) to examine the correlation in performance between corroded reinforced concrete (RC) box culverts and those strengthened with carbon fiber reinforced polymer (CFRP). The research investigated the effects of different corrosion damage thicknesses, ranging from 0 mm to 20 mm, on the structural integrity. The findings indicated that the CFRP-reinforced model demonstrated a significant enhancement in capacity, achieving an increase of 25%, while also exhibiting reduced damage relative to the reference model. In RCCs, the integrity of the bond in steel reinforcement is crucial for structural stability under load. This bond can deteriorate due to environmental exposure, leading to potential failure under increased stress. This research focuses on RCCs' complex, nonlinear behaviour when subjected to static loading, particularly in cases where bond deterioration in terms of is a factor.

By examining how bond deterioration affects the load-bearing capacity and response of RCCs, this paper experimentally examines the structural challenges posed by weakened reinforcement connections and deterioration of culverts, which is often caused by the continuous weathering and water flow on the concrete surface. A Finite Element Model (FEM) using ABAQUS software was also extended to the investigation, which can complement a rigorous and expensive experimental approach. Modeling reinforced concrete in finite element software presents unique challenges due to its complex behavior. An effective material model, however, must capture concrete's dual nature, both its elastic response under low stresses and its plastic deformation under higher loads, in both compression and tension. Achieving this balance is crucial to accurately simulate real-world structural performance, allowing engineers to predict failure mechanisms, crack propagation, and long-term durability of concrete structures under loading conditions. Static General Approach was adopted for the FEM because it efficiently handles non-linear problems, such as plasticity and large deformations, providing accurate results for structural performance under steady loading conditions.

2. Materials and Methods

2.1 Description of RCCs

The moulds used to form the RCC specimens were made of metal. Each specimen's mould comprises dismantlable parts bolted together for easy removal after use, as shown in Figures 1 and 2. The RCCs are in two different shapes, which include circular and rectangular. Each shape is moulded into four different specimens by varying between the types and nature of reinforcing bars used, resulting in eight RCCs as described in Table 1. The outer length of each rectangular specimen is 500 mm, the inner width is 300 mm, and the depth is 300 mm. The outer diameter of the circular specimens is also 500 mm in length, with a width and depth of 300 mm, as illustrated in Figures 1 and 2.

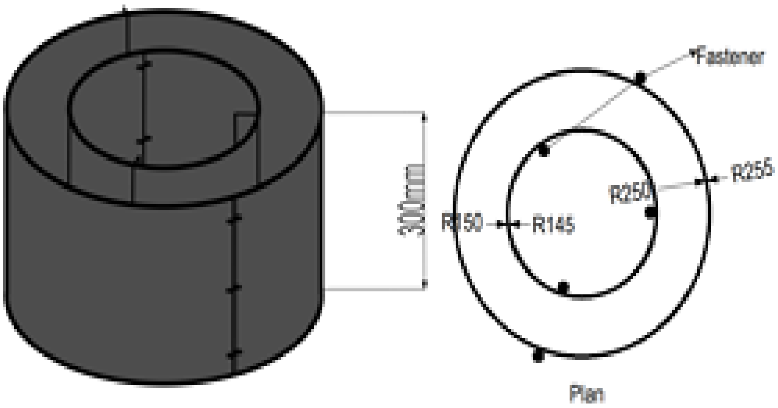

Fig. 1. The cross-section of the fabricated culvert: circular

All the specimens were reinforced with double cages and longitudinal bars, with half of the specimens using Ø6 mm high-yield steel bars, while Ø4 mm steel mesh was adopted for the remaining half, as detailed in Figure 3. Two sets of reinforcement detailing were adopted; the reinforcing bar was arranged without any length cut, while the second was cut as disjointed reinforcement. The vertical distance between the steel reinforcement elements is 50 mm, while the horizontal distance measures 90 mm. The steel mesh also has a vertical spacing of 50 mm and a horizontal spacing of 90 mm. The RCC specimens were cast using a concrete mix ratio of 1:1.5:3

with a water-cement ratio of 0.45, producing grade 20 concrete. The cast culverts are shown in Figure 4. After casting, the specimens were cured for 28 days in a curing bag with a continuous water supply.

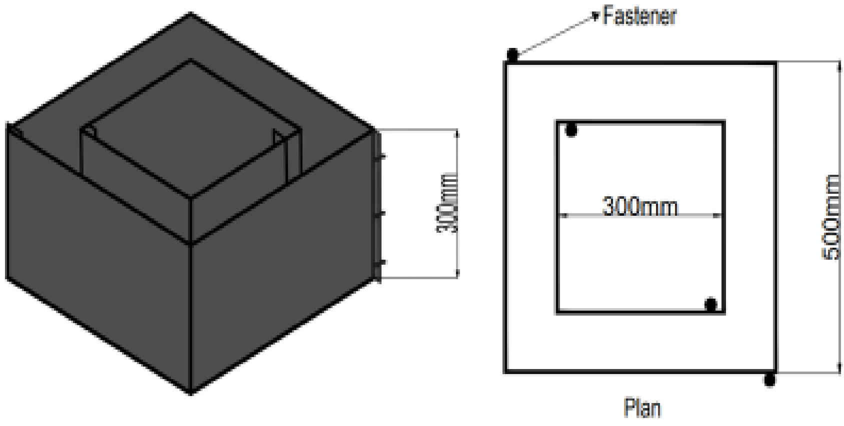

Fig. 2. The cross-section of the fabricated culvert: rectangular

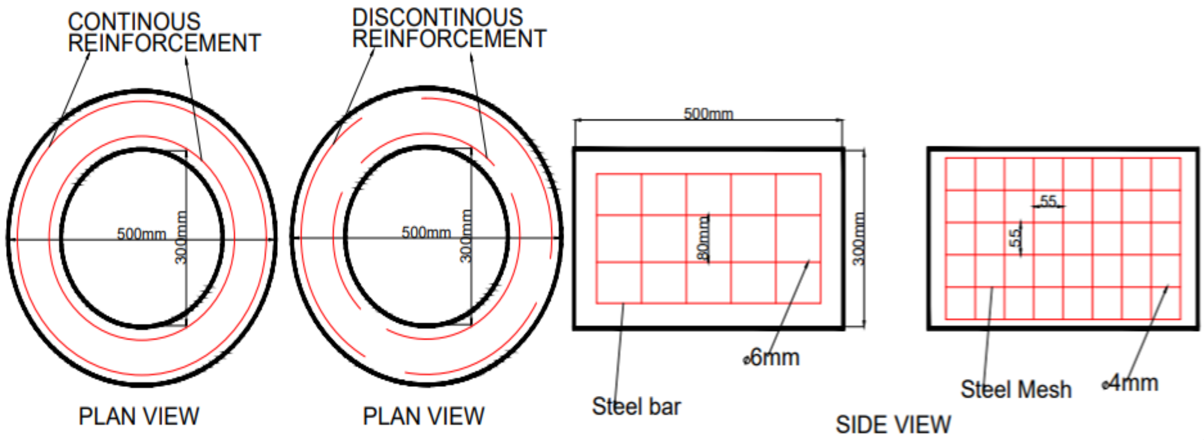

Fig 3. Detailing of the steel reinforcement and mesh in the concrete

Fig. 4. Freshly molded concrete culverts [12]

Table 1. Description of the culvert's specimens

S/N	Nomenclature	Description of concrete culvert	Reinforcement type	Shape
1	RJS	Rectangular with jointed steel bars	Steel bar	Rectangular
2	RDS	Rectangular with disjointed steel bars	Steel bar	Rectangular
3	RJM	Rectangular with jointed mesh	Mesh	Rectangular
4	RDM	Rectangular with disjointed mesh	Mesh	Rectangular
5	CJS	Circular with jointed steel bars	Steel bar	Circular
6	CDS	Circular with disjointed steel bars	Steel bar	Circular
7	CJM	Circular with jointed mesh	Mesh	Circular
8	CDM	Circular with disjointed mesh	Mesh	Circular

2.2 Experimental Load Setup

The RCC specimens underwent a step-by-step loading process using a 300 kN capacity Universal Testing Machine (UTM), designed to push each culvert to its breaking point. To ensure stability, each specimen was anchored securely on the UTM platform, with a steel plate positioned at the top to distribute the load evenly, as shown in Figure 5. The loading rate was maintained at a steady 10 kN per minute, allowing for precise observation of structural responses. Throughout the loading sequence, deflections were recorded, and any visible cracks appearing in different parts of the culvert were marked for analysis. Specific regions subjected to tensile and compressive forces were noted, providing insight into the culvert's performance under stress.

Fig. 5. Testing of concrete culvert

Following a 28-day curing period, the concrete cubes and cylindrical specimens were taken out of the water and left in a controlled room-temperature environment for 24 hours to allow any excess moisture to naturally dissipate. The cubes were then subjected to a compressive strength test using a 1000 kN capacity testing machine. Steel plates were carefully placed on the top and bottom surfaces of each cube to ensure a uniform load distribution during testing. The load was increased step-by-step until the cubes ultimately fractured. For the tensile testing of the cylindrical specimens, each was carefully positioned upright between two steel plates, with the side surface facing the applied load. A gradual load application followed, leading each specimen to its breaking point. This approach provided insight into both compressive and tensile strength characteristics of the concrete specimens.

2.3 Finite Element Model

2.3.1 Geometry Modelling

The Eight (8) RCCs as described in Table 1 were also assessed using FEM, four of which are rectangular and the remaining four are circular. The reinforcement material used is the T3D2: A 2-noded linear 3-D truss element type and for the concrete, three-dimensional (3D) solid elements (C3D8R: An 8-noded linear brick element type) were utilized as provided in ABAQUS.

2.3.2 Mesh, Surface Interaction and Boundary Conditions

In the FEM model, it is essential to maintain a uniform mesh as much as feasible, with the size being approximately determined by a global mesh seed interval. This study employs a uniform global mesh size of 25 mm, which provides both accurate numerical results and a reasonable computation time. This mesh size applies to both the concrete elements and the reinforcement bars, each with a mesh diameter of 25 mm, as illustrated in Figure 6. The rebar elements were embedded in the culvert surface element to create an interaction between the reinforcement and the concrete. The bottom of the culverts was made to interact properly with the supports by using the 'tie' constraint provided in ABAQUS. The supports were effectively fixed because they represented the fixed condition during the experimental test by setting the U_x, U_y, and U_z displacements to zero. These boundary conditions were applied to the middle bottom line of the supports.

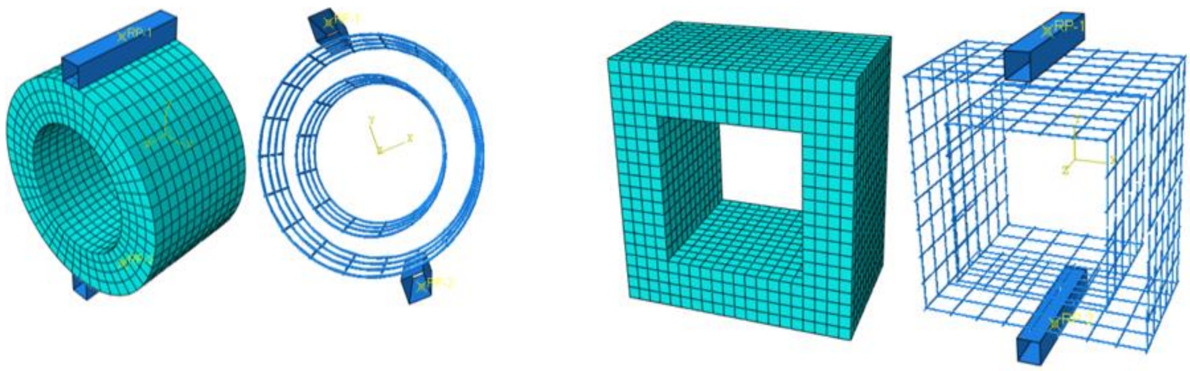

Fig. 6. 3D FE models for culverts in Abaqus: Circular (left), Rectangular (right)

2.3.3 Applying Loads

The load is defined in the step module as 'a static general type'. The load of each specimen is applied as a concentrated displacement on the top support to avoid stress concentration problems.

2.4 Concrete Behavior Model

The smeared cracking model (SC), the Concrete Damaged Plasticity model (CDP), and the Brittle Cracking model are the three available techniques for modelling the nonlinear behavior of concrete in ABAQUS. The CDP model was developed by Lubliner *et al.* [13] and extended by Lee and Fenves [14]. It uses the principles of isotropic damaged elasticity and isotropic tensile and compressive plasticity to represent the non-elastic properties of concrete. It is assumed that the main reasons for failure are the development of tensile cracks and the crushing of the concrete material under compression [15]. The CDP model is utilized in this research because it enhances stability in numerical computations. Certain parameters define the CDP model in ABAQUS, including the elastic and five plastic parameters. In Table 2, the elastic parameters are the modulus, concrete strength obtained from laboratory test and the Poisson ratio; the remaining values are plastic parameters, which are ABAQUS default parameters. This includes the dilation angle (ψ), which impacts volumetric strain, ranging from 0° for brittle behavior to a maximum of 56.3° for highly ductile behavior. 30 – 40 is recommended by researchers [16]. The viscosity (μ) measures the model's rate-dependence, and 0.0001 is recommended. The biaxial-to-uniaxial compressive strength ratio (f_{b0}/f_{c0}) indicates the relative strength of concrete under biaxial loading compared to uniaxial loading, with a default value set at 1.16. Flow potential eccentricity (ε), which represents the ratio of tensile to compressive strength, is recommended to have a default value of 0.1. Additionally, the parameter K_c defines the shape of the failure surface, which should not be circular, with a recommended default of 0.667. These parameters are established in ABAQUS to facilitate the accurate modelling of concrete behavior. The parameters used in modelling the steel are summarized in Table 3.

Table 2. Mechanical properties of concrete modeling

Parameter	Value
Viscosity	0.0001
K	0.667
Dilation Angle	30
Eccentricity	0.1
Mass Density (N/mm^3)	2.4×10^{-6}
fb_0/fc_0	1.16
Poisson's Ratio	0.2
Initial Stiffness (N/mm)	2.2×10^4
Tensile Strength (N/mm^2)	2.48
Compressive strength (N/mm^2)	22

Table 3. Mechanical properties of the steel bars

Parameter	Yield stress (f_y) (MPa)	E_s (GPa)	Poisson's ratio	Density (kg/m^3)
Value	250	210	0.3	7,850

3. Results and Discussion

3.1. Comparison of the Damage Mode Between the Experiment and FEM

Reinforcement deterioration was modelled using discontinuous bars to represent bond loss in the bars. While this approach captures key mechanical implications, it does not fully reflect the complex processes of actual corrosion, such as material degradation and rust-induced cracking. This simplification represents a principal limitation and should be considered when interpreting the applicability of the findings to real-world conditions.

In the experimental and FEM analysis, the RCCs exhibit similar damage patterns. The cracking and failure are concentrated around key structural areas, particularly the crown, invert, and spring line as labelled in Figure 7. In the experimental setup, visible cracks at the crown and inverts suggest tensile stresses exceeding the concrete's tensile strength [17,18], this is likely due to compressive forces combined with the shear effects of loading [12,19].

The experimental and FEM analysis results of the concrete culverts have been evaluated; the FEM analysis was done using the 3-dimensional Concrete Damage Plasticity Model. Figures 7 and 8 illustrate the principal strain damage for the rectangular culvert reinforced with jointed steel and mesh, respectively. Compression damage was first noted at the crown and invert of the culverts, similar to the experiment, which was linked to the fixed bottom and the applied displacement at the crown. This damage occurred at crack loads of 15 and 12 kN for the experiment and FEM reinforced with steel bar (Figure 7) and 10 and 8 kN for the experiment and FEM of mesh reinforcement in Figure 8, respectively. As the load increased, joint cracks developed, causing more deflection and leading to tensile damage at 21.6 kN, 20 kN and 16.7 kN, 14 kN, respectively.

Figures 9 and 10 depict the damage modes from the experiment and FEM analysis of the circular culverts, reinforced with jointed steel and mesh, respectively. The damage mode under the experiment agrees well with the FEM, compression cracking was first observed in the crown and invert. Circular culverts with steel bars experienced crack initiation at a capacity of 7kN and 9 kN for the experiment and FEM analysis, while the crack emerged on the culverts reinforced with mesh at a capacity of 10 and 8 kN respectively. An increase in the applied force increases the damage to double the initial cracking capacity before the total failure occurs at 12kN and 11kN for the culverts reinforced with steel while at damage load of 13 kN and 12 kN. Table 4 shows the initial and failure loads of the culverts under evaluation.

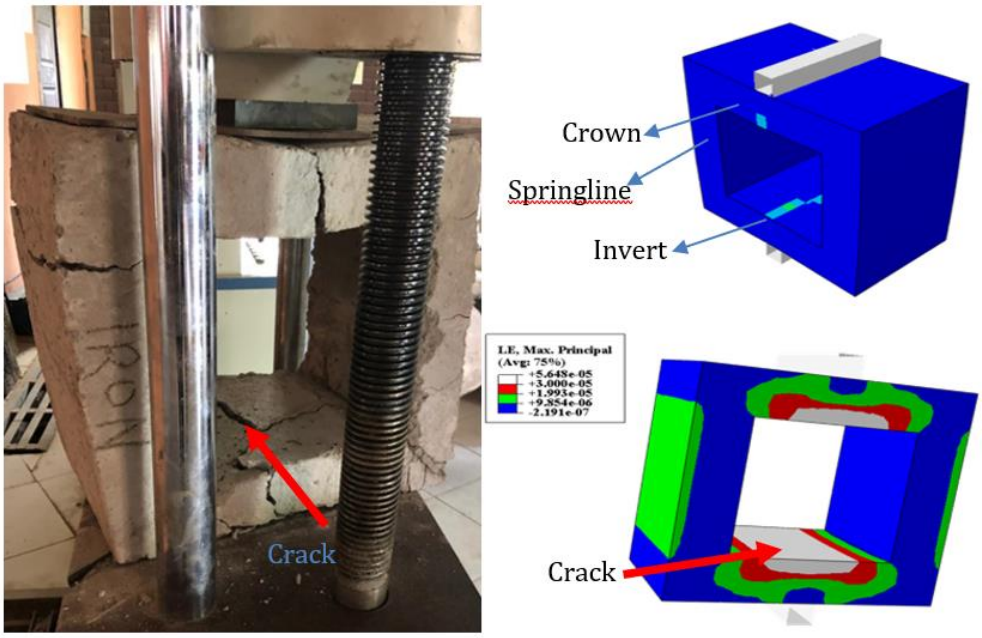

Fig. 7. Damage mode of the rectangular culvert with jointed steel bars (RJS) from experimental test (left) and FEM analysis (right)

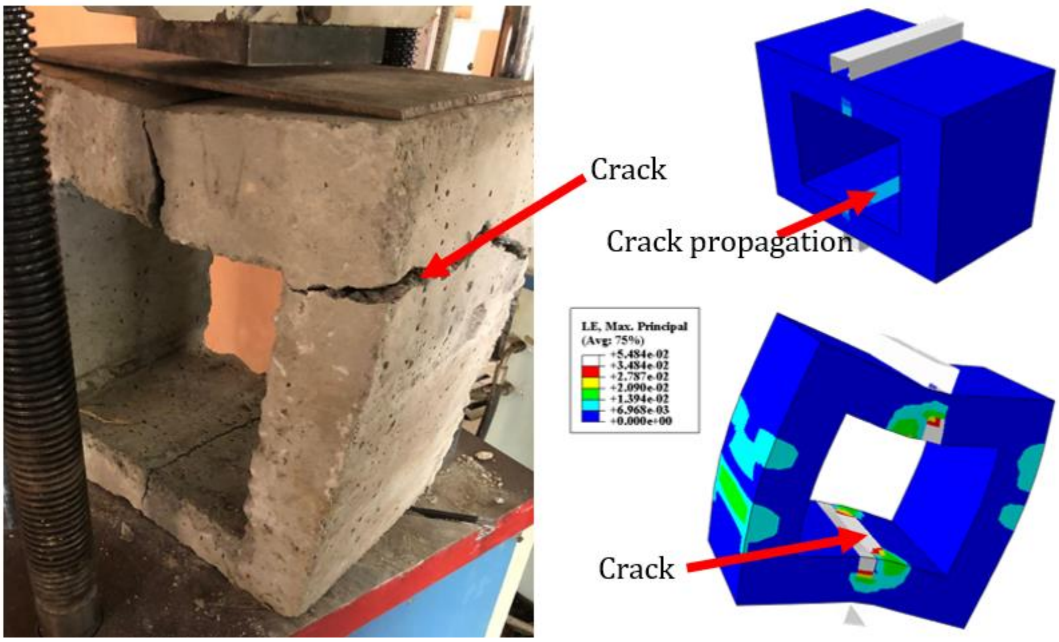

Fig. 8. Damage mode of rectangular culvert with jointed mesh, (RJM) from experimental test (left) and FEM analysis (right)

The damage modes of culverts with disjointed reinforcement, illustrated in Figures 11 to 14, reveal the impact of reinforcement discontinuity, which leads to greater deflection and more extensive cracking. For rectangular culverts, FEM analysis in Figures 11 and 12 show that compression cracking began beneath the loading point at 9 kN for steel-reinforced culverts and 8 kN for those reinforced with mesh, respectively. This is followed by the formation of tension cracks at 15 kN for the disjointed steel and 11 kN for the mesh reinforcement, ultimately causing brittle failure. Subsequently, for the experimental culvert reinforced with disjointed mesh, the crack began under the load of 9 kN, with the emergence of another crack at the spring line at 10 kN. The culvert deflected prominently at 11 kN. The culvert got damaged at 12 kN with a crack found at the bottom, as shown in Figure 11. Meanwhile, in the experimental rectangular culvert reinforced with disjointed steel at the left of Figure 12, the crack began at the crown at 7 kN with an increase in width. An increase in the load resulted in another crack at the spring line at about 8 kN. Then, a crack was observed at the invert at a load of 11kN.

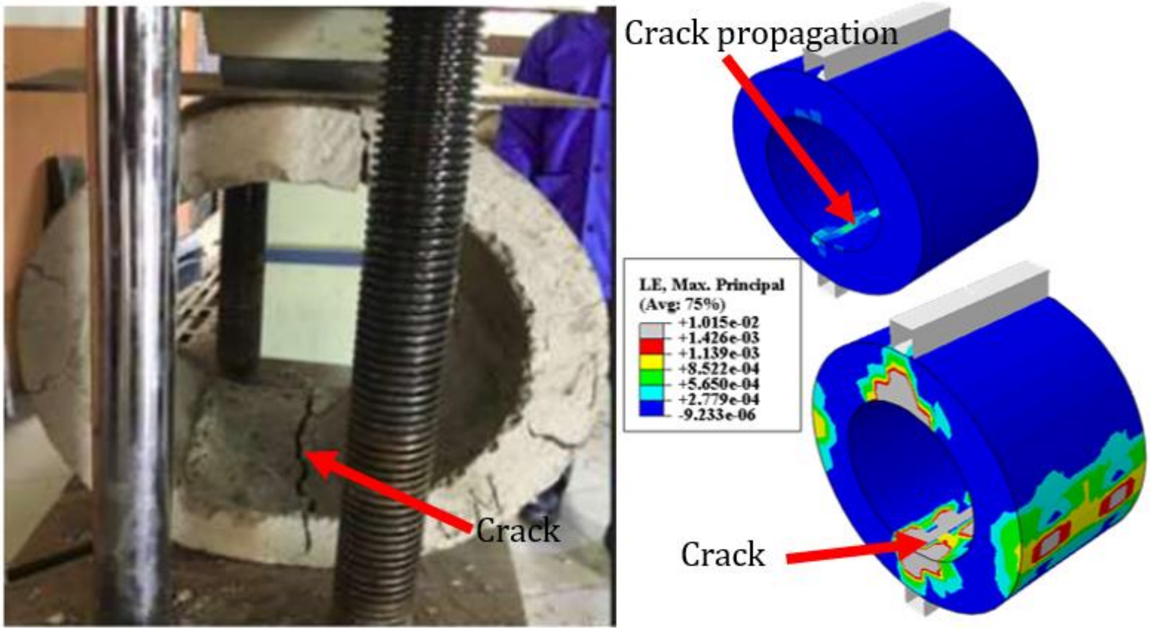

Fig. 9. Damage mode of circular culvert with jointed steel bars (CJS) from experimental test (left) and FEM analysis (right)

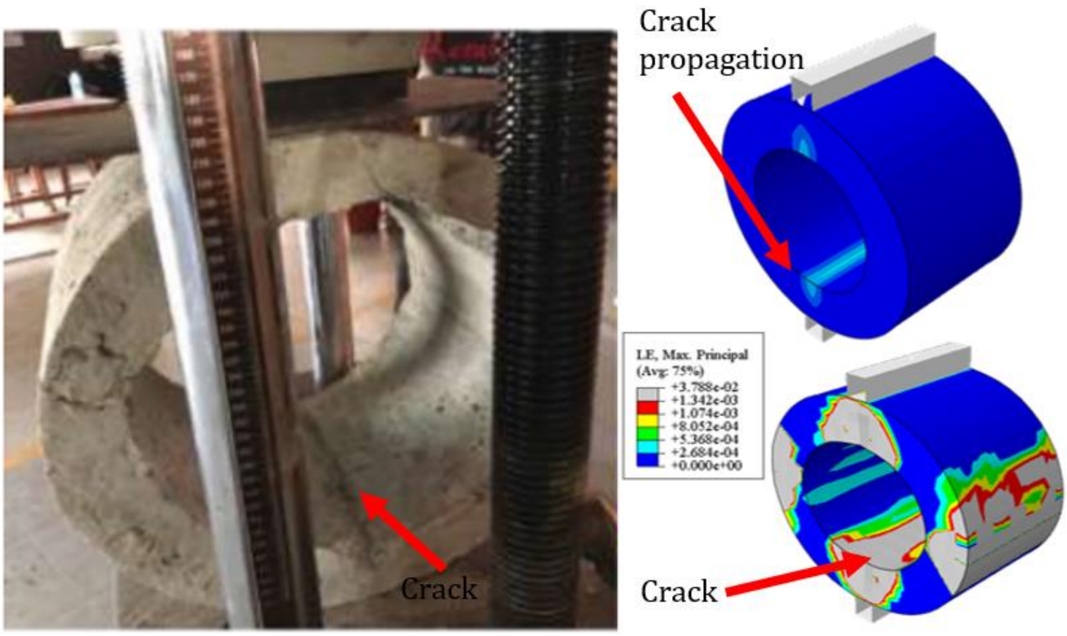

Fig. 10. Damage mode of the circular culvert with jointed mesh (CJM) from experimental test (left) and FEM analysis (right)

In the circular culverts, depicted in Figures 13 and 14. For the FEM, compression cracking was also initiated at the invert beneath the loading point, appearing at 11 kN for steel reinforcement and 8 kN for mesh. Subsequent tension cracks emerge at the spring line at loads of 18 kN and 15 kN for steel and mesh reinforcement, respectively. In the case of the experimental analysis of the circular concrete culvert reinforced with disjointed mesh and steel, the crack was initiated at about 11 kN, 4 kN, while damage occurred at 20 kN and 6.7 kN, respectively. Table 4 presents a comparative analysis of experimental and Finite Element Method (FEM) results for the initial cracking, ultimate failure and the ductility after the failure load measured by the displacement at peak load loads of eight culvert specimens with varying reinforcement conditions. The FEM of RDM and CDS has better ductility than the counterpart experiments. These observations highlight the influence of reinforcement continuity on the load-bearing capacity and failure modes of culverts, with disjointed reinforcement contributing to premature cracking.

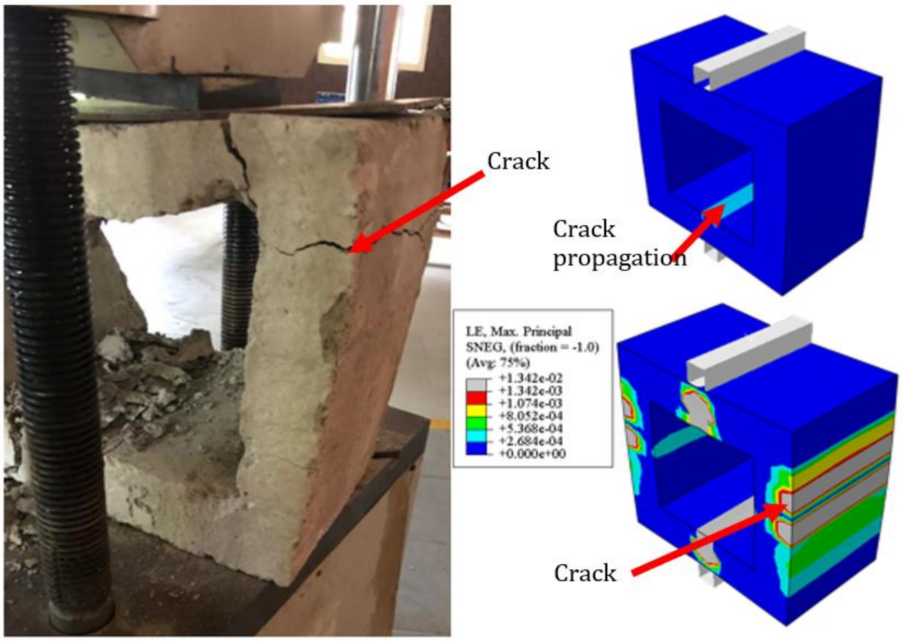

Fig. 11. Damage mode of the rectangular culvert with disjointed mesh (RDM) from experimental test (left) and FEM analysis (right)

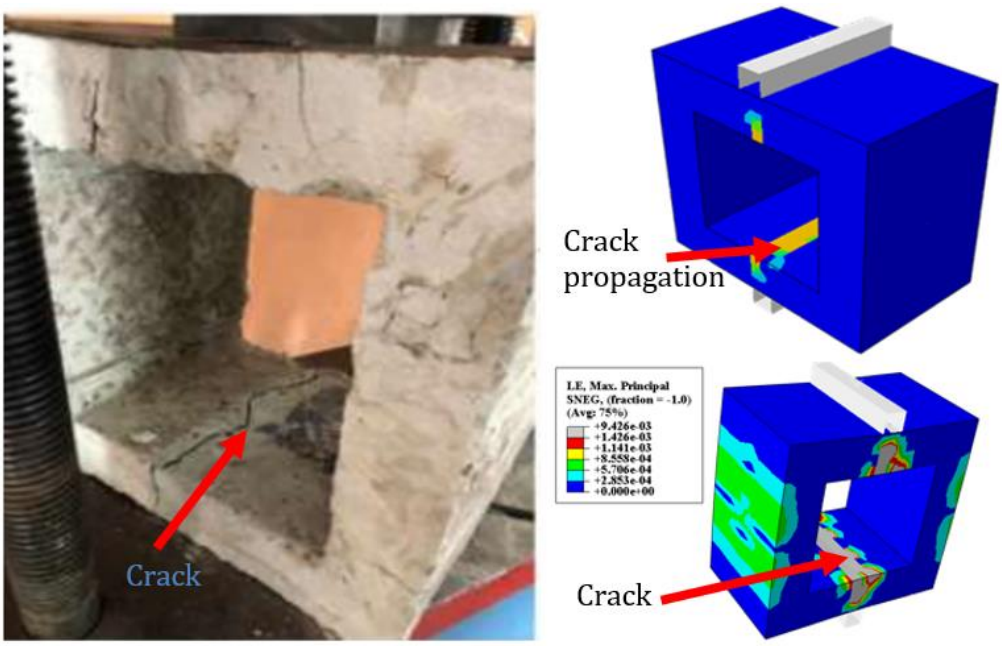

Fig. 12. Damage mode of the rectangular culvert with disjointed steel bar (RDS) from experimental test (left) and FEM analysis (right)

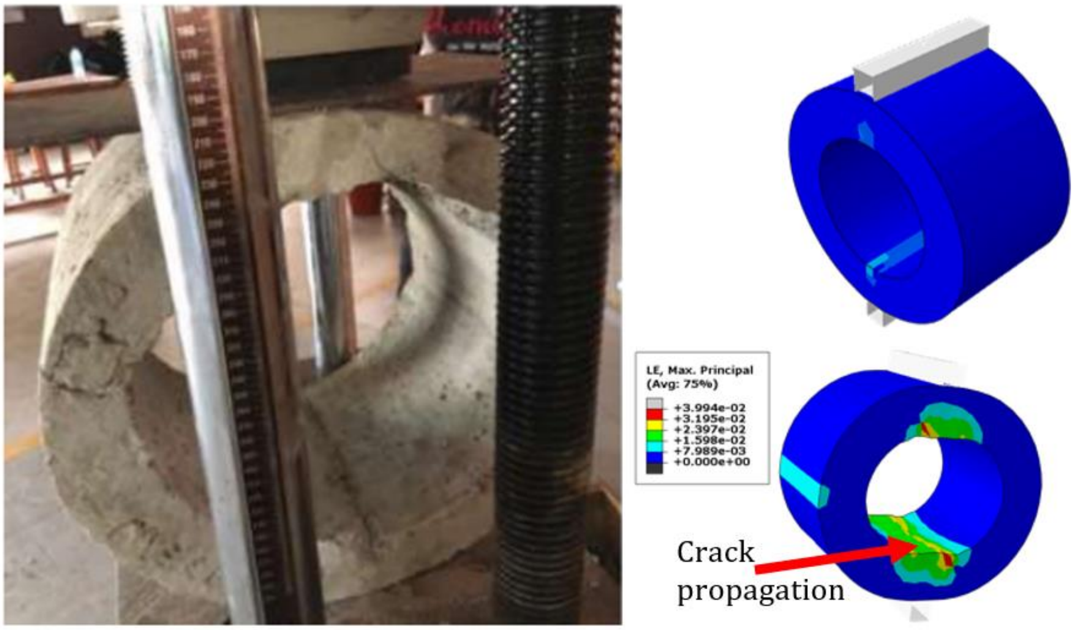

Fig. 13. Damage mode of the circular culvert with disjointed mesh (CDM) from experimental test (left) and FEM analysis (right)

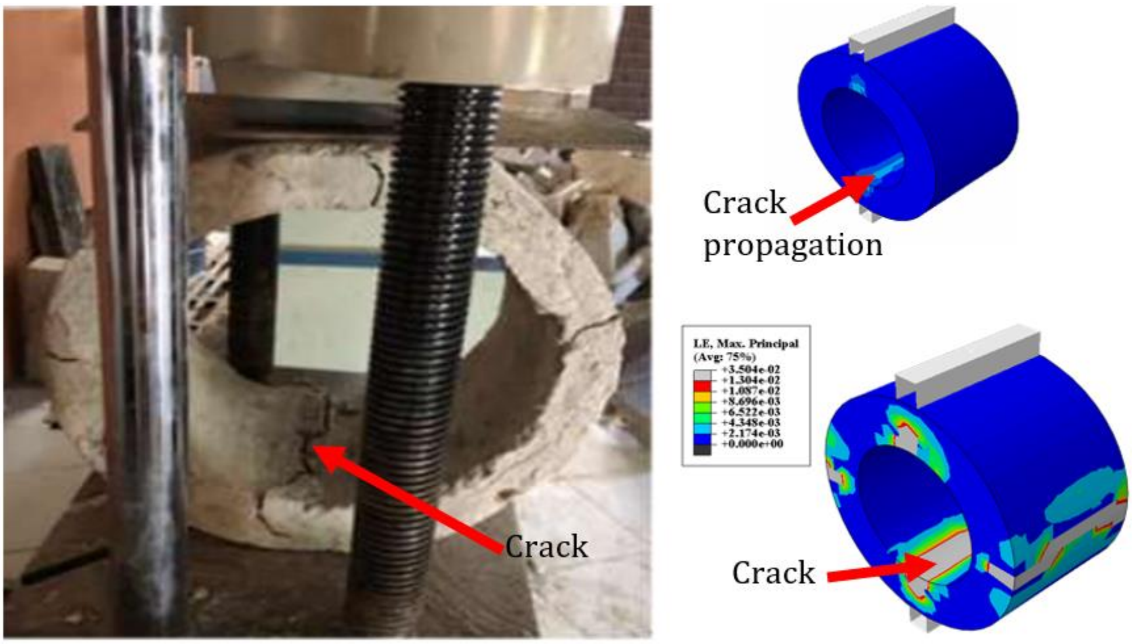

Fig. 14. Damage mode of the circular culvert with disjointed steel bar (CDS) from experimental test (left) and FEM analysis (right)

Table 4. Comparison of experimental and FEM results for initial cracking and failure loads of culverts, with absolute and percentage deviations

S/N	Type	Initial cracking load (kN)			Failure load (kN)			Percentage difference In failure load	Percentage difference in ductility at failure load
		Exp.	FEM	Abs. Dev	Exp.	FEM	Abs. Dev		
1	RJS	15	12	3	21.6	20	1.6	7.4	10.2
2	RJM	10	8	2	16.7	14	2.7	16.1	48
3	CJS	7	9	2	12	11	1	8.3	400
4	CJM	10	8	2	13	12	1	7.6	5.3

5	RDM	9	8	1	12	11	1	8.3	92
6	RDS	7	9	2	11	15	4	36.36	15.5
7	CDM	7	8	1	13	15	2	15.3	44
8	CDS	11	11	0	20	18	2	10	100
Mean				2			1.9	13.7	

3.2 Load versus Displacement Curve Results

The displacement behavior of the reinforced concrete (RC) culverts under static loading was investigated numerically and validated against experimental results. The load–displacement relationships from the finite element model (FEM) closely aligned with the experimental data, as shown in Figures 15–18. Figure 15 illustrates the load-displacement response of rectangular RC culverts reinforced with either steel bars (RJS) or welded mesh (RJM), without the influence of bond deterioration. The culverts reinforced with steel bars (RJS – Exp., RJS – FEM) exhibited a higher ultimate load capacity compared to those reinforced with mesh (RJM – Exp., RJM – FEM), indicating better structural performance.

In contrast, Figure 16 presents the behavior of similar culverts incorporating disjointed reinforcement (deteriorated bond). Both steel- and mesh-reinforced culverts demonstrated reduced load-carrying capacities relative to those in Figure 15. This reduction is attributed to the impaired bond between the reinforcement and concrete, which negatively affected the overall integrity of the structure. These findings highlight the significant impact of bond conditions on the structural performance of RC culverts. The inclusion of disjointed reinforcement compromises strength, with steel reinforcement still outperforming mesh under both conditions.

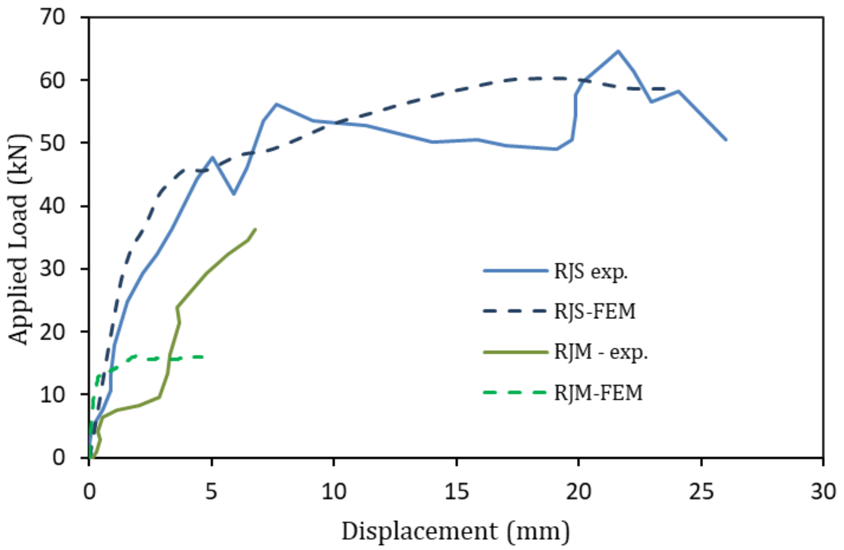

Fig. 15. Load-displacement response of rectangular concrete culverts reinforced with steel bars (RJS) and mesh (RJM) under monotonic loading without bond deterioration: comparison between experimental and FEM results

Figure 17 presents the load versus displacement responses of circular concrete culverts reinforced with either welded mesh or steel bars, excluding the effects of bond deterioration. Specimens CJS and CJM refer to culverts reinforced with jointed steel bars and jointed mesh, respectively, both of which are free from reinforcement discontinuities. Conversely, CDS and CDM (shown in Figure 18) represent culverts reinforced with disjointed steel bars and discontinuous mesh, respectively, thus simulating bond deterioration. As observed in Figure 17, all culverts exhibit a linear load-displacement relationship up to approximately 5 kN, after which the curves diverge under continued monotonic loading. All specimens demonstrate a ductile failure mode, characteristic of reinforced concrete subjected to static load. Comparing Figures 17 and 18, the culvert with disjointed steel bars (CDS) shows a lower ultimate load capacity than its jointed counterpart (CJS), highlighting the adverse effect of reinforcement discontinuity. However, CDS still outperforms

CDM, the culvert with discontinuous mesh, by a margin of 29%, confirming that steel bars provide greater structural resilience than mesh, even under bond deterioration conditions. The concept of reinforcement deterioration refers to the degradation of materials, which includes issues like rust, corrosion, and breaks in the reinforcement. This study focused solely on one specific aspect: a 'break' in the reinforcement, characterized as discontinuous or disjointed rebar. However, this does not fully capture the complexity of real-world deterioration.

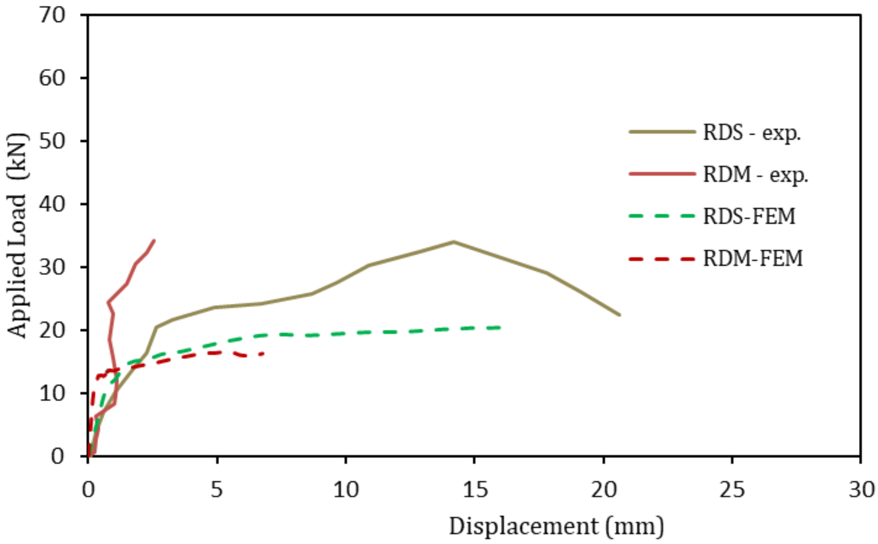

Fig. 16. Load–displacement response of rectangular concrete culverts reinforced with steel bars (RDS) and mesh (RDM) under monotonic loading with bond deterioration: comparison between experimental and FEM results

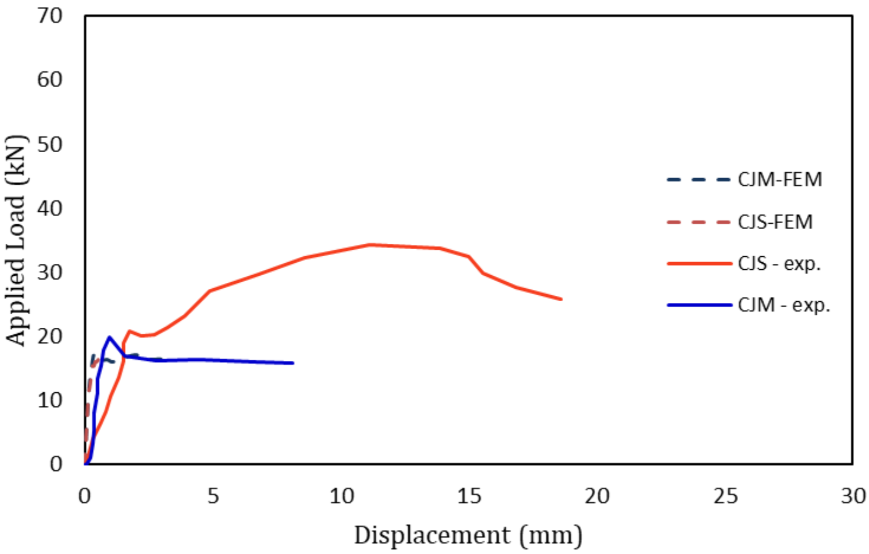

Fig. 17. Load–displacement response of circular concrete culverts reinforced with steel bars (CJS) and mesh (CJM) under monotonic loading without bond deterioration: comparison between experimental and FEM results

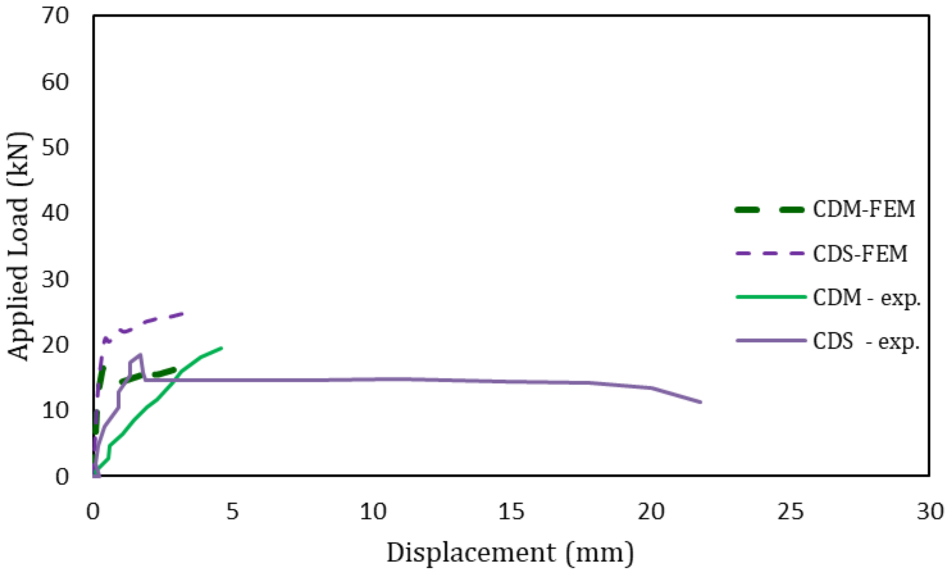

Fig. 18. Load–displacement response of circular concrete culverts reinforced with steel bars (CDS) and mesh (CDM) under monotonic loading without bond deterioration: comparison between experimental and FEM results

4. Conclusions

This research investigated the structural behavior of reinforced concrete (RC) culverts under static loading using both experimental testing and finite element method (FEM) simulations. The primary focus was to evaluate how reinforcement continuity, whether jointed or disjointed, affects load-bearing capacity, damage progression, and overall failure modes in both rectangular and circular culverts. The following conclusions and views were drawn from both experimental and numerical analysis:

- The study revealed that the most prominent damage patterns were consistently located around key structural regions of the culverts, namely, the crown, invert, and spring lines. This was evident in both the experimental tests and the FEM simulations, indicating these zones as the primary stress concentrators during static loading.
- At lower loads, initial damage was predominantly compressive and occurred at the crown and invert. As loading progressed, tensile cracks developed more prominently along the spring line, which aligns with typical structural failure behavior observed in curved or arched RC elements.
- A significant outcome of the study was the pronounced influence of reinforcement continuity on structural performance. Discontinuous or disjointed reinforcement led to earlier crack initiation, higher deflection, and reduced ductility. These culverts exhibited premature tensile damage and lower ultimate load capacity, underscoring the critical role of proper reinforcement anchorage and bonding.
- Culverts reinforced with jointed steel bars, notably RJS (Rectangular Jointed Steel) and CJS (Circular Jointed Steel), consistently outperformed other reinforcement configurations. These systems displayed superior load-bearing capacity, increased ductility, and more stable crack propagation under loading. Notably, RJS demonstrated up to 23% higher failure load compared to the weakest configuration, highlighting the efficiency of continuous reinforcement.
- In contrast, culverts with disjointed reinforcement, such as RDM (Rectangular Disjointed Mesh) and CDS (Circular Disjointed Steel), showed a marked reduction in structural performance. These specimens failed at lower loads and experienced earlier crack propagation and greater deflection, confirming the detrimental impact of inadequate bond continuity between concrete and steel.

- The load-displacement responses obtained from the FEM simulations using ABAQUS closely followed the experimental trends. However, a consistent overestimation was observed in the FEM results, with the average ultimate load capacity predicted numerically being 18% higher than that obtained from the experimental data. This discrepancy can be attributed to the idealised boundary conditions, perfect bonding assumptions, and uniform material properties typically employed in simulations.

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