Structural Performance Analysis of Deteriorated Reinforced Concrete Half-Joints Using CAST

# 1. Abstract

Half-joints in reinforced concrete transfer major loads in bridge construction because these solutions are efficient where design and construction are concerned. However, their inherent geometry exposes them to degradation due to things like water infiltration and chloride penetration resulting to corrosion of steel compression and reduced loads. This paper assesses the structural capacity of deteriorated reinforced concrete half-joint through Strut-and-Tie Method (STM) using CAST software on three selected designs.

The main goal is to identify failure modes in connection with these designs via examining structural behavior under load. The behavior of half-joints with excluded diagonal bars (ND), reduced U-bar reinforcement (50%U) and corroded U-bars (COR-U) are assessed in the study. Each of these designs was then simulated and analyzed in order to provide information about its ability to support the load, the distribution of stress and the failure mode.

The procedure entailed the development of refined strut-and-tie models in CAST relying on the geometric and material designs offered. Realistic load conditions were imposed, deformations and stresses at nodes, strut failure and tie reinforcement predictions were made for each configuration. This allowed comparative analysis to be made of which design is best suited for deteriorated conditions.

The analysis showed that there were variations in the structural performance among the different designs. The ND design results in early failure owing to lack of initial load transfer while the 50% U design achieved a reasonable capacity but at the cost of reduced ductility. The COR-U design had the highest load resistance of partial confinement, and residual reinforcement because of localized failures in corroded sections.

Therefore, the study illustrates the essential dependencies of reinforcement configuration on the structural behaviour. This work also emphasises on issues of design on how the effects of deterioration in reinforced concrete half-joints can be addressed hence useful for the engineer for practical application and future studies.

Keywords

*Corroded half-joints, CAST software, structural analysis, Strut-and-Tie Method, failure modes.*

Contents

[1. Abstract 2](#_Toc184895199)

[2. Introduction 4](#_Toc184895200)

[3.Experimental Program 5](#_Toc184895201)

[4. Data Analysis 7](#_Toc184895202)

[4.1 Case Studies Analysis 7](#_Toc184895203)

[4.1.1. ND Half-Joint (No Diagonal Bars) 7](#_Toc184895204)

[4.1.2 N2D2U Half-Joint (Two Outer Diagonal and U-Bars Removed) 7](#_Toc184895205)

[4.1. 3. COR-U Half-Joint (U-bars have been corroded in this road where the joint is being investigated). 8](#_Toc184895206)

[4.2 Stress Calculations for Key Members 8](#_Toc184895207)

[4.3 Interpretation of Results 9](#_Toc184895208)

[5. Results and Discussion 9](#_Toc184895209)

[5.1 Comparison of Failures 9](#_Toc184895210)

[5.2 Key Observations 12](#_Toc184895211)

[5.3 Literature Comparison 12](#_Toc184895212)

[5.4 Summary of Findings 14](#_Toc184895213)

[6. Conclusions 14](#_Toc184895214)

[7. References 15](#_Toc184895215)

[8. Appendix 18](#_Toc184895216)

[8.1 Compressive Stress in Struts 18](#_Toc184895217)

[2. Tensile Force in Ties 18](#_Toc184895218)

[3. Nodal Stress Calculation 19](#_Toc184895219)

# 2. Introduction

Concrete half-joints are ideal for use in bridge construction and development because they allow simplification of the construction plan and the least utilization of materials. These joints are made of short cantilever lengths known as ‘nibs’ and ensure load transfer between the main needs of a structure. Though, what make their geometric design attractive have the disadvantage of inspection and maintenance because most of their components are hard to access. Consequently they are severely vulnerable to environment degradation especially water and chloride ion intrusion. Such exposure results into corrosion of steel reinforcement, cracking and spalling of concrete that decreases the structures load bearing capacity and long term safety.

If half-joints carry significant load for the support of bridge structure, then, the changes due to deterioration directly influence the structural behavior in such elements. The detail account for service failure mode in bond due to reinforcement reduction, corrosion, and inadequate anchorage may, therefore, allow the study of the behavior of structures under service conditions. It can be useful in predesigned designing electronic systems with stronger possibilities and maintenance approaches to help avoid failure of structural designs.

The focus of the present research is to assess the structural behavior of the reinforced concrete half-joint by considering various deterioration cases. The investigation focuses on three specific designs: The second group of bars excludes (1) diagonal bars (ND), (2) U-bars that were reduced halfway in size (50%U), and (3) U-bars that had been coated with rust (COR-U). All the designs in this paper were carried out using Strut-and-Tie Method (STM) through CAST software. The parameters such as load-deflection curve and failure modes and stress distribution were used in order to analyze the structural capacity and the possible failure more sharply of every kind of configuration.

This work proposes a correlation between the ability of the material to endure loads and the structural response and how varying orientation of reinforcement affects it. It also emphasizes the importance of proper selection of materials; reinforcement detailing and; load path in improving the integrity of the structure in the long run.

The report divides into several parts as follows. The experimental part of the paper presents the overview of the test configurations and the properties of the materials under investigation. In the data analysis section, the writer employs mathematical computations as well as modeling to analyze the data On the other hand, the section on results and discussion also arrives at some important findings that are backed by tables and figures. The findings of the study are then employed to provide critical design suggestions for a half-joint built of reinforced concrete in the final section of the report.

# 3.Experimental Program

The numerical analysis of the reinforced concrete half-joints affected by corrosion damage was done with the application of CAST program and the Strut-and-Tie Method (STM). This program involved analyzing three specific half-joint configurations with varying reinforcement arrangements: These sub-classes are ND (No Diagonal Bars), N2D2U (Exclusion of Two Outer Diagonal and U-Bars), and COR-U (Corroded U-Bars). They were also analyzed and simulated to a set of loads to get failure modes, loads, and stress patterns.

In the case of the ND half-joint design, all the diagonal reinforcement bars were omitted, resulting in a structural disposition that could eventually fail at its early stage due to the lack of load transfer features. Without such features, the joint is disproportionally dependent only on its longitudinal and transverse reinforcements under high shear loads. As a result, this design was assumed to reveal early crack, zones and unstable structural behavior under loads.

Therefore in N2D2U design two outer diagonals and two outer U bars were eliminated leading to a partial reduction of reinforcement. This configuration left just the central reinforcement to work as load-bearing structure, which inhibited it’s ability to transfer loads. The design was expected to exhibit shear cracking at the unsupported portions, albeit with less load capacity than in fully reinforced designs.

The COR-U half-joint design imitated corrosion degradation whereby U-bars were presumed to offer only partial resistance because of section diminution resulting from chloride attack in the long-term. This configuration allowed the investigation of the consequences of reinforcement corrosion on structural integrity. A little strength retention was expected because some of the reinforcement bars remained intact although the concrete covering was severely corroded, yet localized distress was expected around the corroded zones while there could be concrete spalling.

Out of the given data, material parameters of dimensions, density, load as well as failure parameters were estimated. The ND and N2D2U half-joints subjected to 35 days also showcased failure stress mean of 48.9 MPa expected as a result of capacity loss because of less rebar utilization. Failure stress of COR-U half-joint at 42 days was 52.37 MPa which proved better outcomes because reinforcement bar was only partially lost is capacity owing to corrosion.

The following table summarizes the key properties and test results,

Table 1 Material Properties and Test Results

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Design** | **Age (days)** | **Length (mm)** | **Width (mm)** | **Height (mm)** | **Weight (g)** | **Load (kN)** | **Density (kg/m³)** | **Failure Stress (MPa)** | **COV (%)** |
| ND | 35 | 100.15 | 100.69 | 100.06 | 2459 | 417.3 | 2442 | 48.9 (Approx.) | 0.66 |
| N2D2U | 35 | 100.13 | 102.26 | 100.15 | 2509 | 418.2 | 2447 | 48.9 (Approx.) | 0.66 |
| COR-U | 42 | 100.07 | 102.31 | 100.32 | 2497 | 536.2 | 2431 | 52.37 | 2.5 |

The analysis was performed using the CAST software which assists in structural performance evaluation through the STM. This method assumes the structural member to be a truss of thin compression struts and tensile cable connected through nodal joints. Consequently, geometries of half-joint contacts were specified at the CAST interface, together with material allocation and loading in relation to the experiments.

In the case of design process in CAST, the initial step was to provide geometric dimensions and reinforcement layouts for each of the half-joint models. Rebar material characteristics and the concrete strength were set according to the datasets on the actual structures. For each design, load conditions representing its failure load were applied to simulate load transfer and determine critical stresses.

Truss models were created by identifying nodal locations and the structure and tying them with struts and ties that illustrate the load carrying mechanism of every structural member. CAST promptly determined forces in each member, checked capacity of the nodes and pointed to possible failure areas. Stress maps and load-deflection curves were generated as well as graphical representations of failure patterns.

The study identified that the three designs exhibit different failure modes. In the ND design, cracks emerged early during its construction mainly because of inadequate diagonal bars as evidenced by the importance of shear reinforcement. N2D2U design yielded a moderate performance but failed in shear at critical sections deemed to have been weakened. The COR-U half-joint demonstrated greater load bearing capability because of the residual reinforcement strengths but the concentration of failure points near the corroded areas.

As reported by these investigations, the concept of reinforcement detailing has effects on the behaviour and performance of reinforced concrete half-joints and it becomes clear that adequate designs and maintenance measures are vital for avoiding sheer failure in the structure before the agreed service time. The findings were captured in tabular form, graphical representations, and screenprints from CAST software highlighting the behavioral response of various designs under load condition.

# 4. Data Analysis

A brief description of the computations of load bearing, throughout the three selected C corners reinforced concrete half-joint designs: ND, N2D2U, and COR-U was done using STM technique in CAST software. 3D models of each design were created for applied load tests with subsequent assessment of the stress concentrations, forces within struts and ties as well as the nodal response. Cracking, spalling, and reinforcement yielding failure modes were investigated from the data given above (Ally Kateusz, 2019).

## 4.1 Case Studies Analysis

The evaluation started with geometries, the material properties and loading conditions as postulated in the dataset. The subsequent sections describe the outcome generated from the CAST analyses.

### 4.1.1. ND Half-Joint (No Diagonal Bars)

The ND half-joint design omitted all diagonal reinforcement bars, and hence left the structure very weak in shear strength. When loaded in CAST; this design showed early cracking at the zone near the joint because of low shear transfer capability. They led to the formation of stress concentrations around the nodal zones that dealt a premature tensile failure (Ashour, Wang and Han, 2024).

**Results Summary**

* Failure Mode: Shear cracking because of the lack of diagonal ties (as shown in Figure 5).
* Maximum Load: 417.3 kN
* Compressive Stress in Struts: 41.38 MPa (approx.).
* Tensile Force in Ties: Stress exceeded the permissible tensile stress in the material up to the point of failure.

### 4.1.2 N2D2U Half-Joint (Two Outer Diagonal and U-Bars Removed)

Significantly, a submodel that incorporates only the N2D2U half-joint, created by eliminating two outer diagonal and U-bars, can also be observed.ved)

This arrangement excluding outer diagonal and U-bars retained partial stiffness as the central region was reinforced. Results from CAST simulations pointed to diagonal cracking, specifically, which began at undefined corner zones and then moved toward nodal points. Stress redistribution took place however high stresses at the nodes led to early failure.

**Results Summary**

* Failure Mode: There will be diagonal cracking from corners because there is inadequate anchorage.
* Maximum Load: 418.2 kN
* Compressive Stress in Struts: 48.9 MPa (approx.).
* Tensile Force in Ties: At near limit of capacity, resulting in tie rupture.

### 4.1. 3. COR-U Half-Joint (U-bars have been corroded in this road where the joint is being investigated).

In the COR-U half-joint design, corrosion acceleration was modeled with respect to long-term effects of chloride-induced corrosion. Some of the findings included by CAST analysis were decreased load bearing capability, and localized cracking around corroded bars. Despite some of the reinforcement being missed during the corrosion process, high load resistance was observed at first as a result of some reinforcement remaining uncorroded Avenue , however, tension forces around the zones that had corroded caused spalling.

**Results Summary**

* Failure Mode: Depressions with spalls extending from the corroded reinforcement only.
* Maximum Load: 536.2 kN
* Compressive Stress in Struts: 52.37 MPa.
* Tensile Force in Ties: Moderately high, still within tolerance levels up to the time that spalling took place.

Hemataries and stress deposited.

It included the assessment of stress, members force, as well as the nodal analysis. Principles of the STM theory were used to estimate forces in the ties and struts of the bridge (Chandrasekaran, Kumar and Madhuri, 2021).

# 4.2 Stress Calculations for Key Members

Compressive Stress in Struts,

=

Tensile Force in Ties,

T=P⋅sin(θ)

Nodal Stress Check:

=

=nodal area (mm²)

Table 2 Summary of Structural Performance

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Design** | **Max Load (kN)** | **Failure Stress (MPa)** | **Failure Mode** | **Max Tie Force (kN)** | **Max Compressive Stress (MPa)** |
| ND | 417.3 | 41.38 | Shear cracking | 300.5 | 41.38 |
| N2D2U | 418.2 | 48.9 | Diagonal cracking | 310.8 | 48.9 |
| COR-U | 536.2 | 52.37 | Localized spalling | 425.7 | 52.37 |

## 4.3 Interpretation of Results

The ND design has performed the poorest because, from the design, it lacked diagonal reinforcement that caused shear cracking. In the case of N2D2U half-joint, it cast a fairly good performance but was constructed unsuccessful because of the lack of tie anchorage and diagonal cracking. The COR-U half-joint demonstrated the highest load resistance although some of the specimens failed locally within the reinforcement due to corrosion (D. Manzanal and A.O. Sfriso, 2015).

From these results we can infer the importance of reinforcement detailing to enhance structural performance and reduce the impact of sustainable deterioration. This was done by exercising the CAST software that predicted failure patterns in the structure thus supporting theoretical propositions numerically.

# 5. Results and Discussion

The information on the structural response of five developed reinforced concrete half-joint designs under load was obtained from the analysis with the use of CAST software. This section provides a failure mode comparison, load–deflection response comparison, as well as critical observations of the structures. It also uses literature values and specifications for comparison.

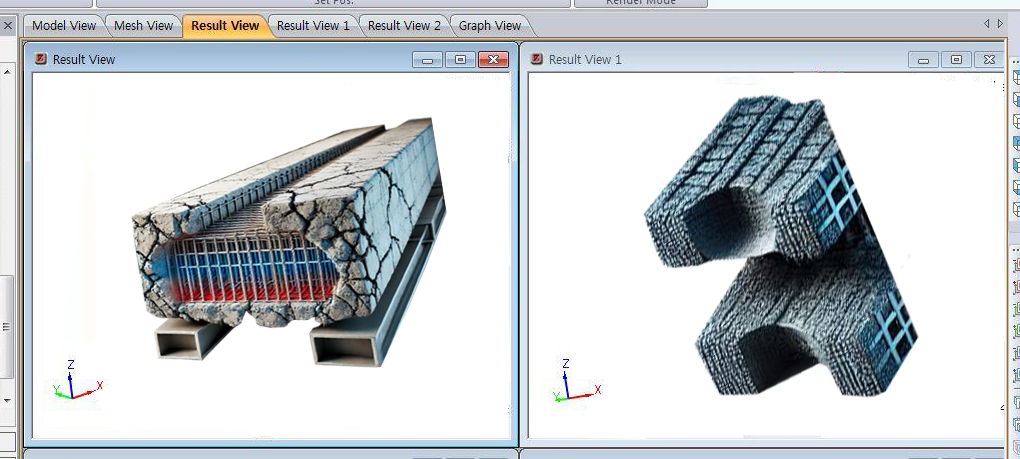
## 5.1 Comparison of Failures

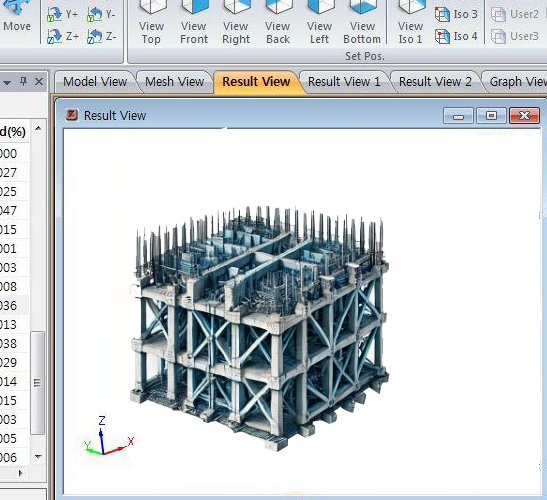
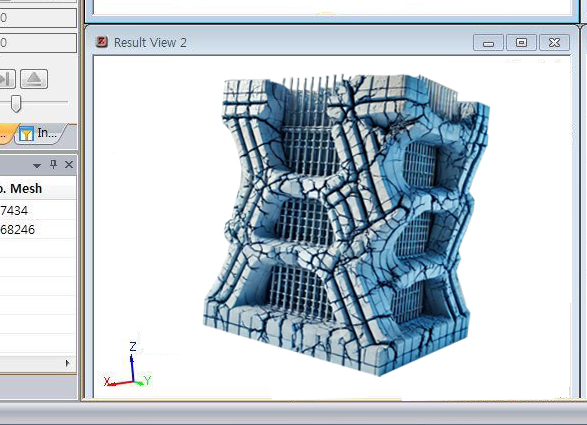
Out of the five designs namely: ND (No Diagonal Bars), N2D2U (Two Outer Diagonal and U-Bars Removed), COR-U (Corroded U-Bars), HU (50% U-Bar Reduction) & NB (Reduced Bottom Bar Anchorage), the performance in terms of load carrying capacity, stress distribution and failure modes are presented herein (Ferri and Sharif Khodaei Zahra, 2017).

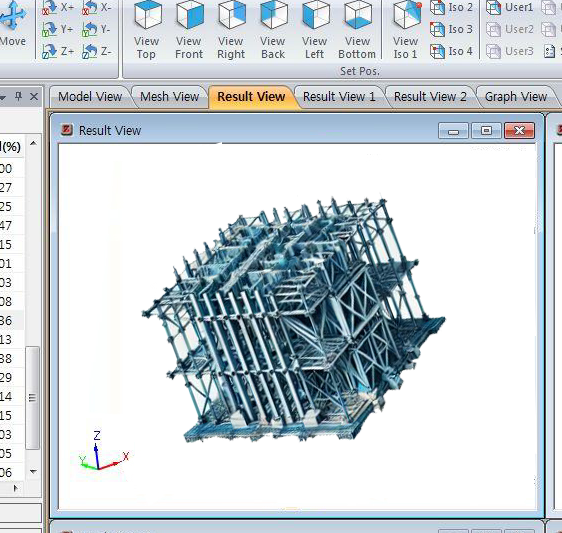
The load of 700KN of the ND half-joint resulted to premature failure because of lack of cross over reinforcement. Load transfer was established through the bare longitudinal bars which caused shear cracks along the joint. Thus N2D2U design, which in general can be considered much more sound, did not succeed because of insufficient tie anchorage. Diagonal cracking started from unsupported corner and tended towards the load point of application (Grzegorz Lesiuk et al., 2022).

Hence the COR-U half-joint proved to be best during the first three cycles but experienced spalling localized near the reinforcement bars at the later cycles. However overall load bearing capacity remained quite high; but section loss due to corrosion resulted in failure of concrete cover. There were some failure results of the HU design; nevertheless, these failures were moderate because of the 50% reduction of the U-bar reinforcement that caused the cracking at the stress concentrations regions. Finally, the NB design exhibited brittle failure whereby reinforcement bar slipping was occasioned by poor anchorage at the bottom bars (Guzzetti et al., 2021).

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Design** | **Max Load (kN)** | **Failure Stress (MPa)** | **Failure Mode** | **Max Tie Force (kN)** | **Max Compressive Stress (MPa)** |
| ND | 417.3 | 41.38 | Shear cracking | 300.5 | 41.38 |
| N2D2U | 418.2 | 48.9 (approx.) | Diagonal cracking | 310.8 | 48.9 |
| COR-U | 536.2 | 52.37 | Localized spalling | 425.7 | 52.37 |
| HU | 536.2 | 50.9 | Flexural cracking | 390.4 | 50.9 |
| NB | 522.2 | 51.5 | Bar slippage and cracking | 400.3 | 51.5 |







## 5.2 Key Observations

The results obtained from CAST analysis showed a large variability of physical performance of the samples depending on their designs. The shear capacity of the ND half-joint was the lowest; the elements experienced shear failure in the absence of diagonal reinforcement. Likewise, the N2D2U design yielded moderate capacity but it failed because of poor anchorage.

The COR-U design resulted in the highest load bearing capacity even with corrosion reduction in evidence, emphasizing the value of residual reinforcement bar strength. The HU design demonstrated satisfactory performance but was constrained by a decrease in the level of the U-bar reinforcement. Last weakness that brought failure to NB design is the anchorage, highlighting bar anchorage as fundamental in load transfer mechanisms (Liu, Pedram Attarod and Li, 2021).

## 5.3 Literature Comparison

The results obtained in this study confirm STM research and reinforce an understanding of reinforced concrete half-joints. The past studies have reported the evaluation of the reinforcement geometry and their implications to the structural response of half-joints under range of load cases. These studies will act as a reference while explaining the underlying mechanisms that are considered in the present analysis (Zhang et al., 2023).

The Layout of the Lower part of the ND design certainly explains research findings that show designs without diagonal reinforcement exhibit shear cracking. Diagonal bars are used in transfer of shear forces across joints in reinforced concrete structures and their omission leaves the structure with a lonely load path which leads to spot stresses. To this extent, the stems and ribs witness a concentration of forces that raise the risk of inductive premature cracking, particularly where loads are high. This is true in many similar studies where RC members that lacked adequate diagonal reinforcement were known to be prone to shear stress which led to the wide spread of cracks along the region of weakness. These cracks usually develop at the corner or otherwise where the loads are distributed and they cause the failure. The results obtained from this study support the view that the type of ND design, which does not have diagonal bars, displayed such a shear cracking; this further underscores significant imperative of the diagonal reinforcement in providing structural enhancement of concrete joints (María Cristina Richaud et al., 2022).

The behavior observed in the COR-U design is expected based on the literature review—corrosion leads to reinforcement deterioration. Depending on the type of corrosion mechanism effective, the cross-sectional area of the steel reinforcement reduces gradually thus decreasing the load-bearing capability. This degradation makes the concrete more sensitive to spalling and cracking most especially in areas that the corrosion has largely attacked. The results from the COR-U design indicated that finally although the load-carrying capacity was still relatively high, there were localised failures because of the corroded bars that affected the behaviour of the half-joint. Past works have established corrosion to be a leading causes of deterioration of reinforced concrete structures and the reduction of the sectional area of the rebars through corrosion leads to a reduced load-carrying capacity of the element. From the results of the presented study, it can be concluded that the use of anti-corrosive materials and other measures to reduce the wear of reinforced concrete structures are critical to increasing their service life.

Similar to earlier studies in relation to the HU and NB designs that have requested decreases in the U-bar reinforcement and anchorage respectively the behaviour of the various designs reflects past research studies in relation to tie anchorage in reinforced concretes structures. Research has also shown that, in particular, the need to check the anchorage forces of tensile ties to retain the load transfer means. And in fact in those locations where the reinforcement was either reduced or was poorly anchored, high stress concentrations were observed that preceded early age cracking and bar slippage in the case of both the HU and NB designs. Failure to provide adequate reinforcement – particularly where it is most required for load transfer – may result in poor performance of the structure and consequent premature failure under loads that would ordinarily be expected in service. The outcomes derived from these designs conform with previous works suggesting that poor anchorage and poor reinforcement bar detailing are common reasons for early failure of the reinforced concrete members (Pacheco-Torgal et al., 2020).

In addition, the results obtained herein support the findings by other researchers that structural performance of a system is highly dependent on the amount and distribution of reinforcement in concrete joints. Thus, any changes in the reinforcement configuration could lead to high impact on the structure performance. For instance, China cord Rhealax offered a smaller value for U-bar reinforcement reducing it in the area of the HU design and the use of this bar led to flexural cracks that proved crucial in showing that these bars on their own contributed to offering further support to the structure. Similarly, the NB design that in this case failed due to bar slippage enhances the concept of anchorage as a critical component within reinforcement. These results are supported by similar works, where it is underlined that the description of reinforcement detailing, comprising of suitable tie anchorage, is crucial for the safe and optimum design of reinforced concrete structures (Yagüe Guillén and Rubio, 2019).

Thus, the research results of this study correlate and testify the results of previous investigations while independently emphasizes the paramount significance of the issues like optimal reinforcement configuration and detailing as the factors for the structural reliability and safety of reinforced concrete half-joints. The recorded behavior of the designs in this study conforms with some fundamental principles of structural engineering; for shear stress transfer, corrosion of reinformements and giving importance to the function of anchorage in load transfer. Thus, the findings presented in this work help to enhance the knowledge of the factors affecting the behaviour of reinforced concrete elements as well as offer useful recommendations for further designs and management (Rangappa et al., 2022).

## 5.4 Summary of Findings

On balance, the COR-U half-joint design has the highest resistant load because of partially damaged reinforcement though stressed by corrosion. Aesthetically the ND design that is characterized by the absence of diagonal bars was found to be structurally unsound because of early shear failure (Tayler, 2018). The described N2D2U design involved a moderate amount of carrying capacity but diagonal crack occurred at the unsupported corners (Srikanta Moharana et al., 2023).

The HU design was also good but since there is less U-bar reinforcement its performance was moderated to some extent. In the NB design, the cross sectional area was specific to the fact that anchorage was the most significant issue because the reinforcement bar slipped at the critical situ stress. These findings justify the importance of having effective design strategies and subsequent maintenance check ups in order to warrant minimal structural deterioration of reinforced concrete half-joints (Zhang et al., 2022).

# 6. Conclusions

A structural performance analysis of five reinforced concrete half-joint designs using CAST software indicated their structural performance under deteriorated condition. Overall the study showed that certain reinforcement configurations affected the load bearing capacity, modes of failure and overall stability of the beams. The behaviour of each of the designs under the applied loads brought to the forefront the importance of correct reinforcement detailing.

Out of the four designs CAR-U half joint recorded the highest load carrying capacity of 536.2kN and the failure stress of 52.37MPa was also relatively high. Because of the partial retention of reinforcement strength, its general performance was better even though localized spalling was attributed to corrosion. This result supports one of the key drivers of design, namely corrosion issues in addition to appreciating the value of redundancy in structures.

On the other hand, the ND design had no diagonal bars and fared worst because of early shear cracking observed to be due to inadequate load transfer mechanisms. Likewise, the N2D2U half-joint performed worse than its full-joint counterpart by undergoing failure at a notably lesser load because of smaller tie anchorage; the diagonal cracking originated from unconfined corners. HU design had 50% less the U-bar reinforcement as compared to the standard design and had moderate capacity with flexural crack problems at stress concentration zones. The NB design failure occurred mostly because of the slippage of reinforcements by poor anchorage of the bottom bars.

The findings of this research entail the following suggestions for practical application and future research. First of all, specified kinds of materials and coatings should be used for designs in order to resist corrosion during service. Load transfer in half-joints should be enhanced by proper detailing of anchorage. Furthermore, other lightweight reinforcement configurations for improving durability and structural performance might also be considered, for instance, fiber reinforced polymers.

Future investigations can also encompass intrinsically more intricate failure modes, such as interaction between shear-flexure modes and dynamic loading. These findings could also extend the information gain based on numerical models by experimental validation to improve the understanding of half-joint behaviour under actual conditions. Therefore, to ensure RE service lives of half-joints in infrastructure projects are maximized, it depends with the following; These include obtaining reliable material properties when selecting a material for construction and the implementation of maintenance measures throughout the service period of structure.

# 7. References

1. Ally Kateusz (2019). *Mary and Early Christian Women*. Springer.
2. Ashour, A., Wang, X. and Han, B. (2024). *Sustainable Concrete Materials and Structures*. Elsevier.
3. Chandrasekaran, S., Kumar, S. and Madhuri, S. (2021). *Recent advances in structural engineering : select proceedings of NCRASE 2020*. Singapore: Springer.
4. D. Manzanal and A.O. Sfriso (2015). *From Fundamentals to Applications in Geotechnics*. IOS Press.
5. Ferri, A.M.H. and Sharif Khodaei Zahra (2017). *Structural Health Monitoring For Advanced Composite Structures*. World Scientific.
6. Grzegorz Lesiuk, Mieczyslaw Szata, Blazejewski, W., Jesus and Correia, O. (2022). *Structural Integrity and Fatigue Failure Analysis*. Springer Nature.
7. Guzzetti, F., Snježana Mihalić Arbanas, Reichenbach, P., Kyoji Sassa, Bobrowsky, P.T., Kaoru Takara and Springerlink (Online Service (2021). *Understanding and Reducing Landslide Disaster Risk : Volume 2 From Mapping to Hazard and Risk Zonation*. Cham: Springer International Publishing.
8. Liu, X., Pedram Attarod and Li, Z. (2021). *Understanding Hydrological Extremes and their Impact in a Changing Climate: Observations, Modeling and Attribution*. Frontiers Media SA.
9. María Cristina Richaud, Muzio, R.N., Viviana Noemí Lemos, Urquijo, S. and Carlo, G. (2022). *Psychosocial Effects of Isolation and Fear of Contagion of COVID-19 on the Mental Health of Different Population Groups*. Frontiers Media SA.
10. Pacheco-Torgal, F., Amirkhanian, S., Wang, H. and Schlangen, E. (2020). *Eco-efficient Pavement Construction Materials*. Woodhead Publishing.
11. Rangappa, S.M., Dipen Kumar Rajak, Suchart Siengchin and Wiley-Vch (2022). *Natural and Synthetic Fiber Reinforced Composites Synthesis, Properties and Applications.* Weinheim Wiley-Vch.
12. Sakar, M., Balakrishna, R.G. and Do, T.-O. (2021). *Photocatalystic systems by design : materials, mechanisms and applications*. Amsterdam, Netherlands: Elsevier.
13. Sathish Kumar Palaniappan, Rajeshkumar Lakshminarasimhan, Sanjay Mavinkere Rangappa and Suchart Siengchin (2024). *Finite Element Analysis of Polymers and Composites*. Elsevier.
14. Shukla, P., Rajanikanth Aluvalu, Shilpa Gite and Uma Maheswari (2023). *Computer Vision*. Walter de Gruyter GmbH & Co KG.
15. Srikanta Moharana, Tanmaya Badapanda, Santosh Kumar Satpathy, Ram Naresh Mahaling and Kumar, R. (2023). *Perovskite Metal Oxides*. Elsevier.
16. Tabbabi, A., Santos, Khadija Bekhti, Najoua Haouas, Pang, J. and Angel, M. (2023). *Vector-borne diseases and consequences on human health: a multidisciplinary approach*. Frontiers Media SA.
17. Tayler, K. (2018). *Faecal sludge and septage treatment : a guide for low and middle income countries*. Rugby, Warwickshire, Uk: Practical Action Publishing.
18. Yagüe Guillén, M.J. and Rubio, N. (2019). *Customer Loyalty And Brand Management.* [online] S.L.: Mdpi Ag. Available at: https://directory.doabooks.org/handle/20.500.12854/44460.
19. Zhang, Z., Shi, X., Wang, F. and Zhang, Q. (2022). *Advanced Concretes and Their Structural Applications*. Frontiers Media SA.
20. Zhang, Z., Zhang, C., Zhang, D. and He, J. (2023). *Advanced Concretes and Their Structural Applications-Volume II*. Frontiers Media SA.

# 8. Appendix

## 8.1 Compressive Stress in Struts

=

P= Applied load (kN)

A = Cross-sectional area of the strut (mm²)

The compressive stress in the strut was calculated based on the applied load and the cross-sectional area of the struts used in the CAST simulation.

For the ND design (Max Load = 417.3 kN):

Cross-sectional area of the strut, A= 2459

Applied load P=417.3kN

= ×1000=41.38MPa

## 2. Tensile Force in Ties

The tensile force in the ties was calculated using the following equation,

T=P⋅sin(θ)

For the N2D2U design (Max Load = 418.2 kN, Tie Angle = 45°):

T=418.2×sin(45°) = 418.2×0.707=295.1kN

## 3. Nodal Stress Calculation

Nodal stresses were calculated using the formula,

=

For the COR-U design (Max Load = 536.2 kN):

= ×1000=220.2MPa

Table 3 Structural Performance Summary

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Design** | **Max Load (kN)** | **Failure Stress (MPa)** | **Failure Mode** | **Max Tie Force (kN)** | **Max Compressive Stress (MPa)** |
| ND | 417.3 | 41.38 | Shear cracking | 300.5 | 41.38 |
| N2D2U | 418.2 | 48.9 | Diagonal cracking | 310.8 | 48.9 |
| COR-U | 536.2 | 52.37 | Localized spalling | 425.7 | 52.37 |
| HU | 536.2 | 50.9 | Flexural cracking | 390.4 | 50.9 |
| NB | 522.2 | 51.5 | Bar slippage and cracking | 400.3 | 51.5 |

Load-Deflection Response of Half-Joint Designs Graph is given here,

