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Structural Investigation of Pipe Sleeve Errors in RC Beams Using FEM: A Case Study

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Abstract: *This study investigates the structural implications of improperly placed pipe sleeves in reinforced concrete beams, a common construction oversight with serious consequences. Motivated by a real-world site error, five cases were simulated using finite element analysis with varying sleeve material, size, and location. The analysis focused on midspan deflection and stress distribution in the pipe sleeve and surrounding concrete. Results show that proper placement of a GI pipe sleeve resulted in moderate stress, while relocating it to a critical section significantly increased normal and shear stresses. Although flexible PVC sleeves reduced internal pipe stress, they transferred greater stress to the surrounding concrete when improperly placed. The findings highlight the need for multidisciplinary coordination and adherence to design specifications. FEA proved effective for visualizing stress patterns and evaluating localized weaknesses, demonstrating its value for both design validation and post-construction assessment for structural, MEPF, and site engineers.*

Keywords: Pipe sleeve; beam; structural; investigation; FEM

1. INTRODUCTION

In typical reinforced concrete (RC) construction, various building systems such as mechanical, electrical, plumbing, and fire protection require a network of pipes that must be accommodated within the structure. A common practice is to install these service lines below the slab and beam soffits, then conceal them with suspended ceilings for aesthetic and functional services [1,2]. While effective, this approach increases the overall floor-to-floor height and can lead to higher material and construction costs.

To reduce this overhead space and achieve a more compact structural layout, another practical method involves providing pipe sleeves through RC beams. These sleeves, which are typically cylindrical openings with diameters slightly greater than the pipes they house, allow the utilities to pass through the beam without direct contact with the concrete.

The placement of pipe sleeves within RC beams must be done with careful consideration to avoid compromising structural performance. Introducing openings or penetrations in beams can lead to increased stress concentration around the pipe sleeve area, particularly under loading conditions. These localized stresses may significantly reduce the beam's stiffness and shear capacity [3]. Moreover, the presence of a pipe sleeve alters the tensile and shear stresses in the concrete surrounding the opening, which could accelerate cracking or failure if not properly accounted for [4,5].

To mitigate these risks, standard engineering guidelines are provided in construction documents and general notes, specifying acceptable pipe sleeve dimensions and locations. Commonly accepted provisions include the following: (1) the minimum center-to-center spacing between pipe sleeves should be no less than three times the pipe sleeve diameter; (2) the outer dimension of the pipe sleeve should not exceed one-third of the overall beam depth; (3) pipe sleeves must be positioned within the middle third of the beam's depth; (4) pipe sleeves must also lie within the middle third of the beam's clear span; and (5) the total area displaced by pipe sleeves should not exceed 4% of a column's cross-sectional area when applied to columns. In addition, material selection for pipe sleeves is critical; some materials like aluminum, are not permitted to be embedded in concrete due to potential long-term deterioration. Another guideline also recommends the addition of web reinforcement around the pipe sleeve location, as shown in Fig. 1, to help restore strength in the disturbed region and reduce the risk of premature cracking or shear failure.

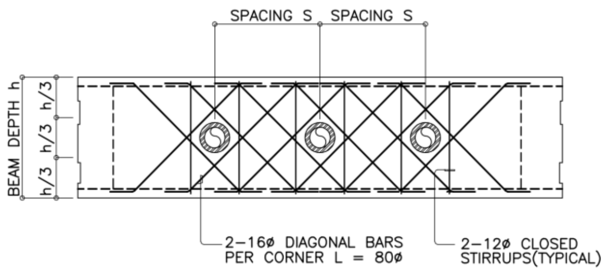

Fig. 1. Typical beam penetration detail.

The construction process is often fast-paced and involves multiple stakeholders working simultaneously to meet project deadlines. In such environments, coordination between trades can sometimes be overlooked. At times, mechanical, electrical, plumbing, and fire protection (MEPF) engineers or subcontractors may proceed with the installation of pipe sleeves or utility lines without consulting the structural or civil engineer. This lack of communication or poor coordination can lead to field modifications that violate approved structural drawings, potentially resulting in the placement of pipe sleeves within structurally critical zones. This was the case in a real-world construction project, where a 75mm Ø PVC pipe sleeve was mistakenly installed in the critical region of an RC beam, an area where penetrations were explicitly prohibited, as shown in Fig. 2. Such deviations raise serious concerns about structural safety, load-bearing performance, and long-term durability of the affected structural element.

Fig. 2. Typical beam penetration detail.

In the real-world construction project referenced earlier, the on-site error involved two critical issues. First, the pipe sleeve was placed in a prohibited location, near the beam-column junction and outside the middle third of the beam's clear span. Second, the pipe sleeve material used was PVC Schedule 40, which contradicts typical material specifications that recommend galvanized iron (GI) or equivalent. These construction errors became the basis and motivation for this study, which aims to investigate the structural implications of such deviations. In addition to these two observed errors, the study also broadens its scope to include another frequently encountered issue on construction site: the use of oversized pipe sleeves. Such deviations, when undocumented or uncoordinated, can significantly compromise the load-bearing capacity of RC members.

This study presents a finite element investigation of RC beams with varying pipe sleeve configurations to evaluate the structural effects of common field errors. Finite element modeling (FEM) has proven effective in the medical field in assessing stress distribution and failure locations in bone structures and other complex materials, as shown in the work of Htun et al. [6], who identified correlations between bone density and stress concentration patterns. Similarly, Salaha et al. [7] demonstrated that geometric changes in structural elements, such as openings and notches, significantly influence stress trajectories and failure zones. These findings reinforce the importance of detailed numerical simulations when evaluating irregularities in RC beams.

Using ANSYS software [8], five beam models were developed based on the actual dimensions and reinforcement details obtained from the observed construction project. The modeling scenarios include: (1) a control beam without any pipe penetration; (2) a beam with a 75 mm Ø GI pipe sleeve placed within the allowable zone; (3) a beam with the same 75 mm Ø GI pipe sleeve incorrectly placed in a structurally critical region; (4) a beam with a 75 mm Ø Schedule 20 PVC pipe sleeve installed in the critical zone, reflecting the actual on-site error; and (5) a beam with an oversized 200 mm Ø Schedule 40 PVC pipe sleeve located in the same critical region. These cases were selected to systematically assess how deviations in pipe sleeve placement, material, and size influence the beam's structural performance under loading. Ultimately, this study aims to bridge the gap between theoretical design assumptions and actual construction conditions. It provides a forensic view into how seemingly minor field decisions can compromise the performance of a structural element.

2. METHODOLOGY

2.1 Problem Formulation

This study is based on an actual construction case as described in the previous section. To investigate the structural implications of this violation, a 6-meter-long simply supported RC beam was modeled in ANSYS [8]. The beam cross-section, reinforcement details, and loading conditions replicate those from the actual project. The applied loading was determined using the tributary area method. A live load of 3.0 kPa, as specified in the National Building Code of the Philippines [9], was considered, along with the beam's self-weight as the dead load. Material properties for reinforcing steel, concrete, GI pipe, and PVC pipe were obtained from relevant standards and are summarized in Tables 1, 2, Table 3, and Table 4, respectively.

Table 1. Steel rebar mechanical properties.

Material Property	Value	Unit
Modulus of elasticity	200000	MPa
Poisson's ratio	0.3	
Tensile yield strength	414	MPa
Compressive yield strength	414	MPa
Tensile Ultimate strength	620	MPa
Compressive ultimate strength	620	MPa

Table 2. Concrete mechanical properties.

Material Property	Value	Unit
Modulus of elasticity	30000	MPa
Poisson's ratio	0.18	
Tensile Ultimate strength	5	MPa
Compressive ultimate strength	28	MPa

Table 3. GI pipe mechanical properties.

Material Property	Value	Unit
Modulus of elasticity	200000	MPa
Poisson's ratio	0.3	
Tensile yield strength	248	MPa
Compressive yield strength	248	MPa

Table 4. PVC pipe mechanical properties.

Material Property	Value	Unit
Modulus of elasticity	2895.8	MPa
Poisson's ratio	0.41	
Tensile Ultimate strength	51	MPa
Compressive ultimate strength	66	MPa

To evaluate the structural impact of pipe sleeves in RC beams, a series of finite element models were developed and analyzed using ANSYS software. Each model represents a different configuration of pipe sleeve placement and material, simulating both standard practice and common construction errors. The details of the modeled cases are summarized in Table 5. Case 1 represents the control specimen without any pipe penetration. Case 2 adheres to standard construction guidelines, serving as the benchmark for acceptable practice. Cases 3, 4, and 5 simulate various construction errors, with Case 4 specifically replicating the actual on-site violation observed in the referenced project that motivated this investigation.

Table 5. Beams with varying pipe sleeve configurations.

Case	With PS	Correct PS location	Material Used	Correct PS diameter
Case 1	No	Yes	GI	Yes
Case 2	Yes	Yes	GI	Yes
Case 3	Yes	No	GI	Yes
Case 4	Yes	No	PVC	Yes
Case 5	Yes	No	PVC	No

2.2 Numerical Modeling

The geometry of the RC beam was developed using ANSYS SpaceClaim. The full beam has a length of 6,000 mm, a width of 400 mm, and a height of 600 mm as shown in Fig. 3. To reduce computational cost while maintaining accuracy, only half of the beam was modeled. Necessary boundary conditions were implemented to simulate the behavior of the full beam.

Fig. 3. Beam dimensions and section details.

The concrete body was modeled using the 'Solid' setting in ANSYS, allowing for accurate representation of volume, and stress distribution. Reinforcing steel bars were defined as 'Beam' elements with 'Circular' beam profiles. The main longitudinal rebars were modeled with a diameter of 25 mm, while the diagonal bars surrounding the pipe sleeve region were assigned a 16 mm diameter following the provisions in Fig. 1. These reinforcement details replicate those observed in the actual field case and ensure realistic structural interaction between concrete and steel within the finite element model.

The beam model was discretized using a structured mesh in ANSYS. A mesh size of 50 mm was used for the general concrete body as shown in Fig. 4. However, finer meshing was applied in critical areas to better capture stress concentrations and local behavior. Around the pipe sleeve, the concrete was assigned a finer mesh size of 25 mm. The pipe sleeve itself, whether made of GI or PVC, also used a 25 mm mesh size. For the reinforcing steel bars, a mesh size of 25 mm was applied as well.

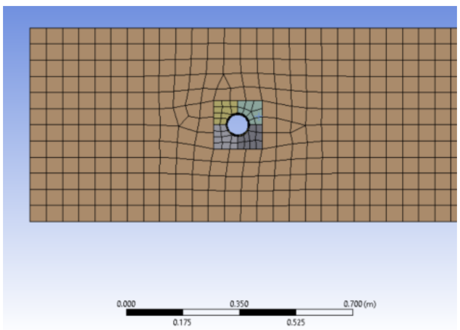

Fig. 4. Mesh of concrete body

To reduce computational cost, only half of the beam is considered in modelling. Boundary conditions were defined to simulate realistic support and loading conditions while accounting for the use of a half-beam model as shown in Fig. 5. The support at one end of the beam was assigned a 'Fixed Support' boundary condition, representing the actual restraint in the field. Since only half of the beam was modeled, a 'Displacement' boundary condition on the opposite end was applied. In this setup, translation along the z-axis (the lengthwise direction of the beam) was constrained to prevent movement, while translations in the x- and y-axes were left free. This simulates the behavior of the full beam while reducing model size and computational cost.

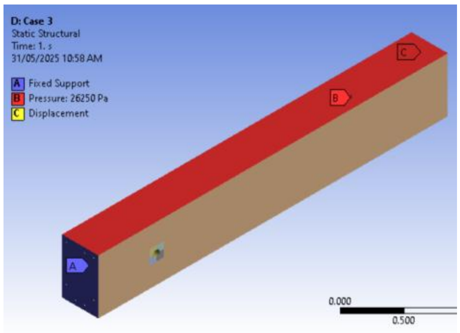

Fig. 5. Boundary conditions

For loading, a pressure load was applied on the top surface of the beam. The magnitude of the pressure was calculated using the tributary area method, combining a live load of 3.0 kPa, as specified in the National Building Code of the Philippines [9], with the self-weight of the beam as the dead load. This loading setup reflects typical floor beam conditions in actual construction scenarios.

The analysis evaluated the structural impact of pipe sleeve penetrations on the reinforced concrete beam. Key results included maximum beam deflection, stress concentrations around the pipe sleeves, maximum normal stress in the concrete, and stress distribution within the GI or PVC sleeves.

3. RESULTS AND DISCUSSION

Table 6 presents the maximum midspan deflection of the RC beams for all five cases. From Case 1 to Case 4, the deflection values remain relatively unchanged, with only negligible variations. This consistency suggests that the presence of a pipe sleeve whether placed or incorrectly did not significantly alter the global stiffness of the beam. This can be attributed to the fact that the sleeve diameters used in these cases, which are 75 mm represent a relatively small portion of the beam cross-section and were not large enough to substantially affect the flexural rigidity of the member.

However, Case 5 exhibited a slightly higher deflection of 0.3671 mm, which is about 3% greater than the control beam, Case 1. This increase, although small, reflects the cumulative impact of two critical deviations: (1) the use of a larger 200 mm Ø pipe sleeve, and (2) its location in a structurally critical region. The combination of a larger void and reduced concrete cross-section in a high-moment zone likely resulted in a slight reduction in stiffness, which explains the marginal increase in deflection. While this deflection is still within acceptable limits, it points to a localized weakening of the beam's flexural behavior when improper sizing and placement of penetrations are combined.

Table 6. Maximum beam deflection at midspan.

Case	Midspan deflection (mm)
Case 1	0.3552
Case 2	0.3553
Case 3	0.3559
Case 4	0.3563
Case 5	0.3671

Table 7. Normal stress in the RC beam.

Case	Maximum Tensile Stress (MPa)	Maximum Compressive Stress (MPa)
Case 1	1.4354	1.3990
Case 2	1.4354	1.3990
Case 3	1.4352	1.3990
Case 4	1.4352	1.3990
Case 5	1.4344	1.3990

The evaluation of normal stresses in the pipe sleeves provides important insights into how the location, material, and the size of the pipe sleeves influence stress distributions in RC beams. The values in Table 8 show clear trends in both tensile and compressive stress across different cases.

Table 8. Normal stress on the pipe sleeve.

Case	Maximum Tensile Stress (MPa)	Maximum Compressive Stress (MPa)
Case 1	-	-
Case 2	0.9430	0.0222
Case 3	3.7077	0.0811
Case 4	0.1244	0.0278
Case 5	0.9367	0.0819

The normal stress observed in the pipe sleeves provides insight into how much the pipe sleeve itself resists under structural loading conditions. High normal stress in the pipe sleeve generally indicates that the pipe sleeve is actively engaging with the surrounding concrete and contributing to the redistribution of internal forces. This behavior is desirable when the pipe sleeve is correctly placed and made of a stiff material, such as GI, as in Case 2. In this case, the stress was moderate which is 0.9430 MPa, suggesting effective load-sharing between the sleeve and the beam without introducing stress concentrations. However, in Case 3, where the same GI sleeve was placed in a critical section, normal stress rose significantly to 3.7077 MPa. This indicates a concentration of stress in an already sensitive region of the beam, likely due to improper placement disrupting the stress flow, which may lead to localized damage or cracking.

In Case 4, a 75 mm Ø PVC Schedule 20 pipe sleeve was placed in a structurally critical region of the beam. This case recorded the lowest normal stress among all pipe sleeve configurations. At first glance, these lower stress values might suggest improved performance; however, they are primarily attributed to the significantly lower stiffness of the PVC material rather than an indication of structural adequacy. PVC, being a flexible thermoplastic with a low modulus of elasticity, absorbs less stress and instead transfers most of it to the surrounding concrete. This lack of stiffness reduces the load-sharing capacity of the pipe sleeve and may result in stress concentrations in the adjacent concrete, increasing the likelihood of cracking and long-term deterioration.

In contrast, Case 5 used a larger, stiffer, and thicker PVC pipe sleeve but still positioned in the same critical region. This case recorded slightly higher stress values compared to Case 4, largely due to the increased cross-sectional area and wall thickness of the Schedule 40 pipe. Nonetheless, despite the improved mechanical properties relative to Schedule 20, PVC still performs poorly in terms of structural compatibility with reinforced concrete. It offers little to no reinforcement benefit, lacks bonding with concrete, and is susceptible to long-term deformation or creep under sustained loading.

These findings reinforce that while PVC pipe sleeves may be suitable for non-critical zones, their use in RC beams particularly in regions near supports should be avoided. GI pipe sleeves, which exhibit significantly higher stiffness and bonding potential, are structurally safer alternatives in such contexts. The analysis of Cases 4 and 5 ultimately illustrates the structural risks of using inappropriate sleeve materials in critical zones and highlights the importance of material selection as part of an integrated structural design and construction process.

Figures 6 to 13 illustrate the normal stress distributions and corresponding deformations of the pipe sleeves for Cases 2 to 5. These visuals complement the tabulated data by showing how stress concentrations and sleeve deformation vary based on material type, sleeve size, and placement.

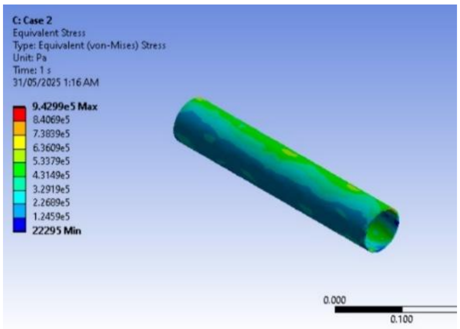

Fig. 6. Normal stress on the pipe sleeve (Case 2).

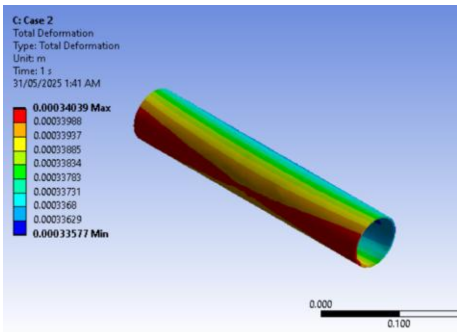

Fig. 7. Deformation on pipe sleeve (Case 2).

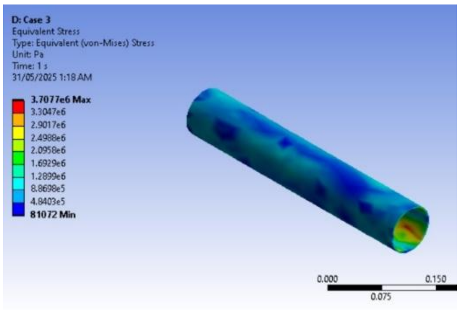

Fig. 8. Normal stress on the pipe sleeve (Case 3).

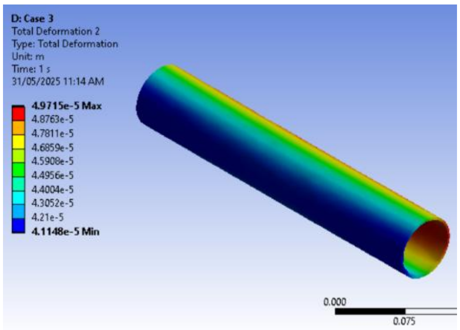

Fig. 9. Deformation on pipe sleeve (Case 3).

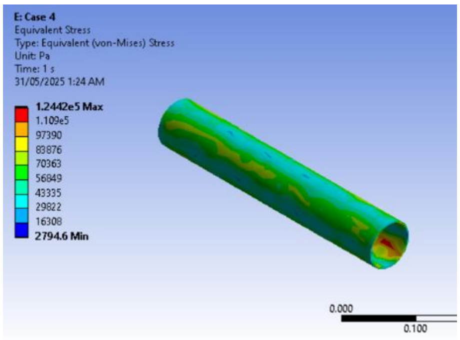

Fig. 10. Normal stress on the pipe sleeve (Case 4).

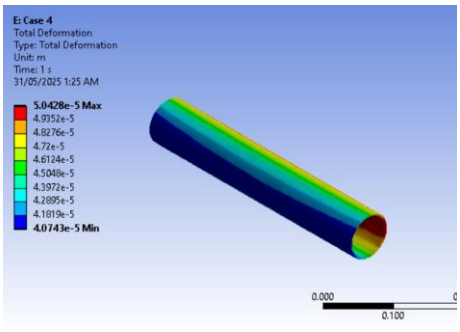

Fig. 11. Deformation on pipe sleeve (Case 4).

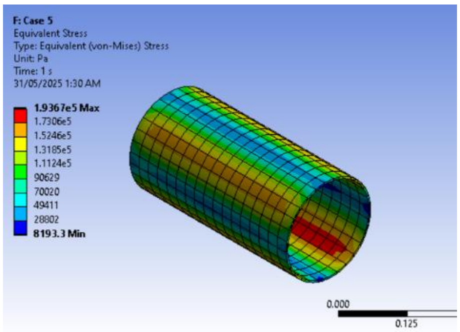

Fig. 12. Normal stress on the pipe sleeve (Case 5).

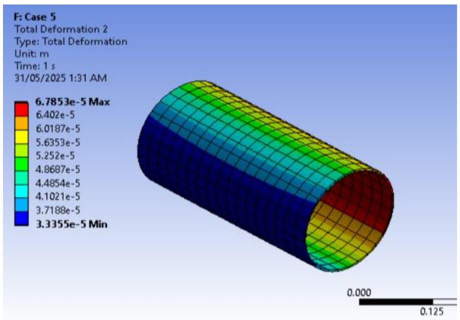

Fig. 13. Deformation on pipe sleeve (Case 5).

Table 9 shows that the maximum shear stress in the RC beam remained nearly unchanged from Case 1 through Case 4, with values consistently around 0.3447 MPa. This indicates that the inclusion of a 75 mm pipe sleeve, whether correctly placed or misplaced in critical regions, had minimal impact on the beam's shear performance especially when located outside major shear zones. These results suggest that moderate-sized penetrations do not significantly disrupt shear stress distribution under typical loading conditions.

Table 9. Shear stress in the RC beam.

Case	Minimum Shear Stress (MPa)	Maximum Shear Stress (MPa)
Case 1	0	0.3447
Case 2	0	0.3448
Case 3	0	0.3447
Case 4	0	0.3446
Case 5	0.0089	0.4680

In contrast, Case 5 exhibited a notable increase in maximum shear stress to 0.4680 MPa. This reflects a substantial rise of approximately 36%, indicating that oversized sleeves in high-shear zones can lead to stress concentrations and reduced shear resistance. These findings emphasize the importance of limiting sleeve size and ensuring proper placement to maintain structural integrity in reinforced concrete beams.

Table 10 shows the maximum shear stresses on the pipe sleeves, revealing a pattern similar to that observed for normal stresses in Table 8. Case 3, with a stiff GI pipe sleeve positioned in a critical beam section, experiences the highest shear stress at 2.0517 MPa. In contrast, Case 4, using a more flexible PVC sleeve in the same location, exhibits a much lower shear stress of 0.07 MPa. Cases 2 and 5, involving properly placed or larger sleeves, show intermediate stress levels. These results emphasize how both material stiffness and sleeve placement critically affect stress concentration on the sleeve, with rigid GI sleeves attracting greater shear forces, especially when placed in critical structural zones.

Table 10. Shear stress on the pipe sleeve.

Case	Maximum Shear Stress (MPa)	Minimum Shear Stress (MPa)
Case 1	-	-
Case 2	0.5021	0.0125
Case 3	2.0517	0.0044
Case 4	0.0704	0.0015
Case 5	0.1095	0.0047

Table 11 highlights the shear stress on the concrete surrounding the pipe sleeves. Cases 3, 4, and 5 show notably higher stress levels compared to Case 2, reflecting the impact of placing sleeves in critical beam sections. In Case 2, with the sleeve correctly positioned outside the critical zone, the concrete experiences significantly lower shear stress, emphasizing the crucial role of proper pipe sleeve placement in preserving the beam's structural integrity.

Table 11. Stresses on the concrete around the pipe sleeve.

Case	Minimum Shear Stress (MPa)	Maximum Shear Stress (MPa)
Case 1	-	-
Case 2	0.1256	0.0502
Case 3	0.5427	0.1875
Case 4	0.5096	0.1986
Case 5	0.8901	0.1174

Figures 14 to 17 present the shear stress distribution in the concrete surrounding the pipe sleeves for Cases 2 to 5. These support the numerical findings by visualizing the increased stress concentrations in the concrete when sleeves are positioned in critical beam regions, especially in Cases 3 to 5.

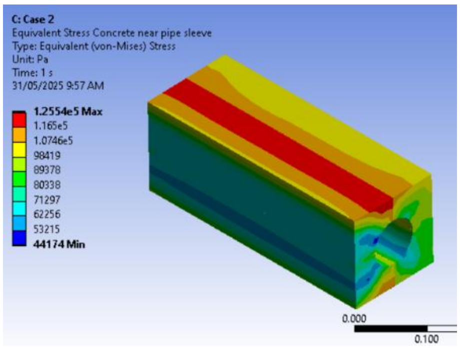

Fig. 14. Stress on concrete near the pipe sleeve (Case 2).

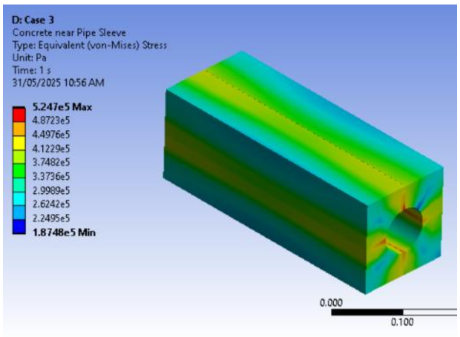

Fig. 15. Stress on concrete near the pipe sleeve (Case 3).

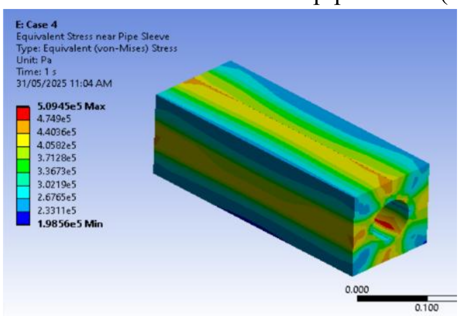

Fig. 16. Stress on concrete near the pipe sleeve (Case 4).

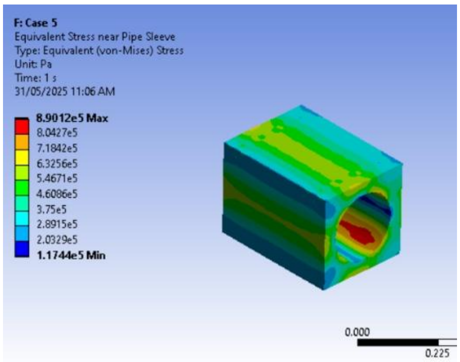

Fig. 17. Stress on concrete near the pipe sleeve (Case 5).

4. CONCLUSION

The study draws its relevance from a real-world construction error and reinforces the importance of multidisciplinary coordination and strict adherence to structural design provisions. By utilizing finite element analysis and presenting visual results, this investigation offers practical insights not only for structural engineers but also for MEPF engineers and site personnel involved in execution. The findings highlight the consequences of miscommunication and field improvisation, particularly in the placement and material selection of embedded pipe sleeves.

Notably, the comparison between Case 2 and Case 3 illustrates the significant structural implications of improper sleeve placement. While Case 2, which placed a GI pipe sleeve within the permissible middle third of the beam span and depth, showed moderate normal stress of 0.9430 MPa and shear stress of 0.5021 MPa on the sleeve, relocating the same sleeve to a critical section in Case 3 resulted in a dramatic increase in stresses which is 3.7077 MPa for normal stress and 2.0517 MPa for shear stress. This clearly demonstrates that even compliant materials can lead to severe stress concentrations when positioned in structurally sensitive zones.

Similarly, although PVC sleeves introduced lower stress in the pipe sleeve material itself due to their flexibility, surrounding concrete experienced higher stress levels when these sleeves were placed in critical sections. This emphasizes that while soft materials may reduce stress within the sleeve, they do not eliminate the structural impact on surrounding concrete.

Overall, this study affirms the utility of FEM in anticipating construction-related issues and enhancing decision-making both before and after implementation.

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