The International Conferences on Engineering Sciences

E-ISSN: 3090-6733

(Research/Review) Article

Assessment of Steel Structure Connections After Fire Exposure Through Bolt Torque Testing and Dye Penetrant Inspection

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Abstract. *In 2022, a significant fire incident occurred at a steel tower structure in an industrial plant in Lampung, Indonesia, raising serious concerns about the structural integrity and serviceability of the affected steel framework. Fire exposure is known to alter the properties of steel, weaken bolt pretension, and cause defects in welds, underscoring the necessity of thorough post-fire assessments. Nondestructive testing (NDT) methods are crucial in evaluating the safety and stability of structures after fire exposure, as they can detect potential weaknesses without compromising the material further. This study employed two field inspection methods: the bolt torque test and dye penetrant inspection (DPI). A total of 21 bolts (Tor-1 to Tor-21) were tested for their integrity. The results showed that, while all bolts were present, more than half were found to be loosened, indicating the need for re-tightening to restore the specified torque and maintain the required preload for the bolted connections. In addition, 20 welded joints (DP-1 to DP-20) were examined using DPI to detect surface defects. The inspection revealed that 10 welds (50%) exhibited surface defects exceeding 5 mm in length, indicating areas where the welds had been compromised by the fire exposure. Seven welds (35%) were found to be in acceptable condition, while 2 welds (10%) were incomplete or had poor bonding. These findings suggest that while the bolted joints can be restored through corrective re-tightening, the welded joints require more extensive evaluation, local repairs, or even rewelding to ensure their structural integrity. This study highlights the importance of NDT methods in post-fire structural evaluations and recommends periodic inspections and targeted rehabilitation to ensure the long-term reliability and safety of industrial steel structures.*

Keywords: *Bolt Torque Test; Dye Penetrant Test; Non-Destructive Test; Post Fire; Steel Structure*

Received: November 29, 2024;
Reviced: Desember 30 2024;
Accepted: January 22, 2025;
Published: January 30, 2025;
Curr. Ver.: January 30, 2025

1. INTRODUCTION

A severe fire occurred in the steel tower structure of an industrial plant in Lampung in 2022, raising concerns regarding the safety and integrity of the existing structure after the incident. The factory owner sought to evaluate the condition of structural connections, particularly bolted and welded joints, in order to determine the post-fire serviceability of the structure (Bisby et al, 2005).

Fires in steel structures can lead to significant alterations in the mechanical properties of materials, including reduced residual strength and permanent deformation. Bolts, as critical fastening elements, are particularly vulnerable to loss of load-bearing capacity when exposed to elevated temperatures, especially in high-strength grades such as grade 8.8. Previous studies have shown that fire exposure combined with post-fire cooling methods substantially influences the tensile and shear capacity of bolts (Zhang et al., 2023)

In addition to bolted joints, welded connections also play a vital role in maintaining the integrity of steel structures. Experimental studies have reported that joints exposed to temperatures exceeding 600°C undergo significant reductions in bonding capacity and deformation behavior (Chen et al., 2024).

Non-destructive testing (NDT) methods are widely applied to assess the condition of structural connections without damaging steel components (Kiran et al, 2019). Bolt Torque Testing enables direct evaluation of bolt tightness in the field (Ali et al, 2001). Dye Penetrant Testing (DPI) effectively detects surface defects in welds, such as cracks or porosity (ASTM E165-18, 2018).

Although numerous studies have examined the mechanical properties of steel after fire exposure, research specifically integrating Bolt Torque Testing and Dye Penetrant Testing in real industrial fire scenarios remains limited. Therefore, this study aims to evaluate the condition of bolted and welded joints in a steel tower structure after a fire using field inspection methods, thereby providing practical insights into the serviceability of structural connections.

2. LITERATURE REVIEW

Mechanical Properties of Steel Material Post-Fire

Fire exposure significantly alters the mechanical properties of steel. At temperatures above 600 °C, steel begins to lose residual strength, experience reductions in elastic modulus, and become susceptible to permanent deformation (Chen et al., 2024). Studies indicate that rapid quenching leads to microstructural changes such as brittle martensite formation, while natural cooling results in slower yet considerable strength degradation (Haiko et al., 2021).

The impact of fire on structural steel also depends on the duration of heat exposure. Experimental findings show that prolonged exposure worsens strength degradation compared to short-term heating at the same temperature (Maraveas et al., 2017). The residual capacity of fire-exposed steel can decrease by up to 50% of its original strength, making post-fire evaluation essential before structural reuse.

Behavior of Bolted and Welded Connections Under Thermal Exposure

Bolted connections are critical elements in steel structures that are highly sensitive to elevated temperatures (Yu et al., 2019). Numerical studies demonstrate that increased heat exposure reduces bolt shear capacity and connection rotation. Uneven temperature distribution and joint gaps significantly affect the stability of bolted joints during fire conditions (Hawkins, 2022).

Welded joints are also strongly affected by high temperatures. Fire exposure can lead to cracking, porosity, and loss of weld bonding strength. Experimental studies show that welded joints exposed to temperatures above 600 °C suffer significant reductions in tensile and shear capacities (Cirpici & Sagiroglu, 2024).

Evaluation of Steel Structures After Fire

Post-fire evaluation aims to determine whether the structure can be safely reused. This process often begins with visual inspection to identify deformations, discoloration, and other indicators of high-heat exposure. Further tests such as hardness testing or tensile testing are frequently employed to measure residual strength (Steel Institute Australia, 2020). Numerical methodologies have also been developed to assess the residual strength of post-fire steel. Thermo-structural simulations can predict changes in strength and deformation behavior of structural elements. This approach aids building owners and engineers in deciding whether structures require strengthening or replacement Lou et al., 2017).

Non-Destructive Testing (NDT) allows inspection of connections without damaging structural elements. Bolt Torque Testing is applied to evaluate bolt tightness, while Dye Penetrant Testing (DPI) is used to detect surface flaws in welded joints. These two methods complement each other in identifying issues in structural connections after fire exposure (ASTM E165-18, 2018, SNI 8458:2017). NDT methods are proven to be effective and economical compared to destructive testing. DPI reveals small surface defects that may trigger failure, while torque testing ensures that bolted joints can still sustain design loads. The combination of both provides a comprehensive understanding of post-fire structural joint conditions.

International standards regulate testing procedures to ensure reliable results. DPI is governed by ISO 3452-1:2013 and ASME Sec V Article 6, outlining pre-cleaning, penetrant application, developer, and inspection steps. Meanwhile, bolt torque testing in Indonesia follows SNI 8458:2017, which specifies torque methods based on bolt diameter. Applying these standards is crucial to make test results comparable across projects and sites. Standardized procedures enhance defect detection accuracy and ensure bolt torque values meet safety requirements. By adhering to official standards, post-fire evaluations provide a robust foundation for technical decision-making (ASTM E165-18, 2018, SNI 8458:2017).

3. METHODS

The primary objective of this study is to evaluate the condition of structural connections in a steel tower after fire exposure by applying nondestructive testing methods in Figure 1. The bolt torque test was conducted to determine whether the bolts retained sufficient pretension and to ensure that bolted joints continued to perform according to standards.

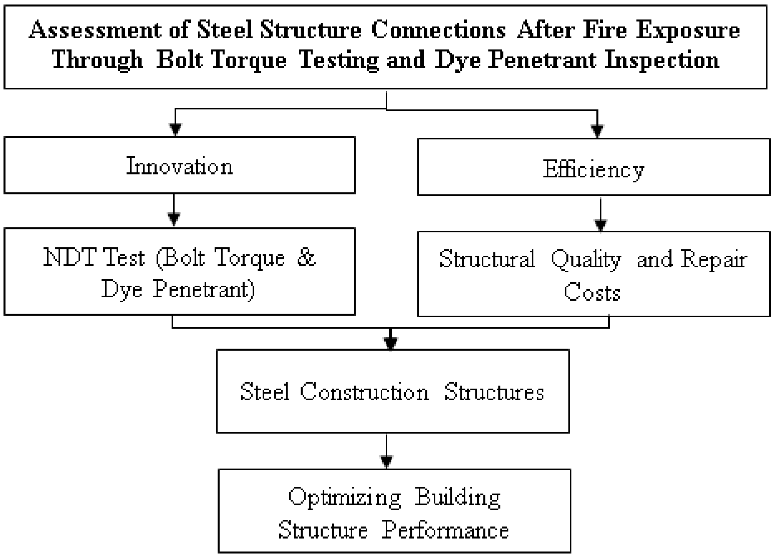


Figure 1. NDT testing framework

The bolt torque test was conducted to verify that clamping force in the connections remained adequate after the fire. The procedure followed SNI 8458:2017, employing portable torque wrenches on randomly selected bolts. Prior to testing, representative joint locations were identified, the torque wrench was calibrated and configured, and the socket size was set to match the bolt head in Figure 2. The wrench was seated squarely and rotated in the tightening direction to obtain the in-situ torque reading. Measurements were recorded on test forms with location IDs and marked in the field for traceability. Where torque fell below the reference value, re-tightening was performed until the specified torque was achieved. Photography documented before–after conditions to ensure a clear audit trail. The method emphasizes applying the correct torque to prevent pretension loss without causing deformation of connection components.

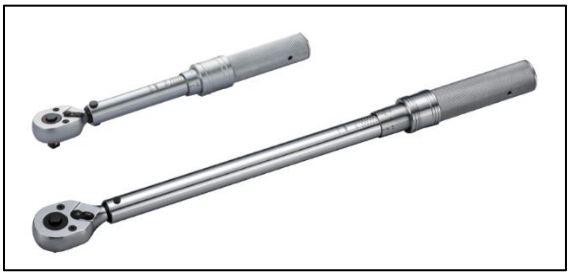


Figure 2. Bolt torque test

The dye penetrant inspection (DPI) was used to detect surface-breaking weld defects based on capillarity, following ASME Section V Article 6. Test areas were cleaned to remove oil, rust, and debris with a minimum 25 mm band around the weld, followed by pre-cleaning using cleaner or remover and 1 minute evaporation period. The penetrant was applied by spray or brush at a surface temperature of 20–50 °C and allowed a minimum 5minute dwell time. Excess surface penetrant was carefully removed using a dry cloth (then a lightly moistened cloth without spraying cleaner directly), and the surface was left ≥1 minute to ≤10 minutes before spraying developer from 15–20 cm after shaking to ensure proper mixing.

Observations were made 10–30 minutes after developer application under illumination of ≥100 fc (1000 lux) verified by a lux meter. All indications were measured and photographed, and assessed against acceptance criteria: linear relevant indications >1.5 mm, rounded relevant indications >5 mm, and four or more rounded indications in line with edge-to-edge spacing <1.5 mm were considered rejectable. Supporting equipment included a stopwatch, inspection lamp, lux meter, steel ruler, infrared thermo-gun, penetrant, cleaner or remover, developer, and PPE in Figure 3. Process parameters (time, temperature, lighting) and results were recorded on inspection forms in Figure 4.

Figure 3. Set developer penetrant test

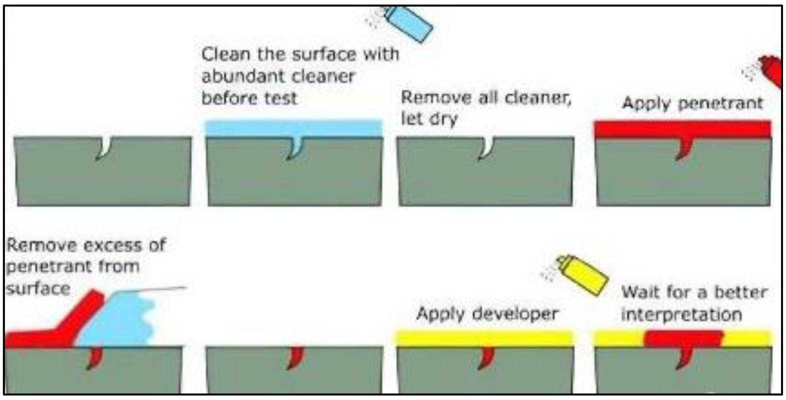


Figure 4. Dye penetration application testing

4. RESULTS

Field testing was conducted on 21 bolt samples (Tor-1 to Tor-21) from the steel tower structural connections. Results indicated that all bolts were complete, with no missing components such as washers or lock nuts in Figure 5. However, it was observed that a significant number of bolts were in a loosened condition during inspection. Corrective action in the form of re-tightening was immediately performed on-site to ensure each bolt achieved the torque values in accordance with the standard.

The bolt torque test results revealed that most bolted joints retained acceptable torque levels according to design standards, yet several bolts displayed torque values below the minimum threshold.

This phenomenon can be attributed to thermal effects during the fire. At elevated temperatures, steel bolts undergo thermal expansion, reducing their initial pretension. Upon cooling, the pretension does not fully recover, leaving the bolts in a loosened state.

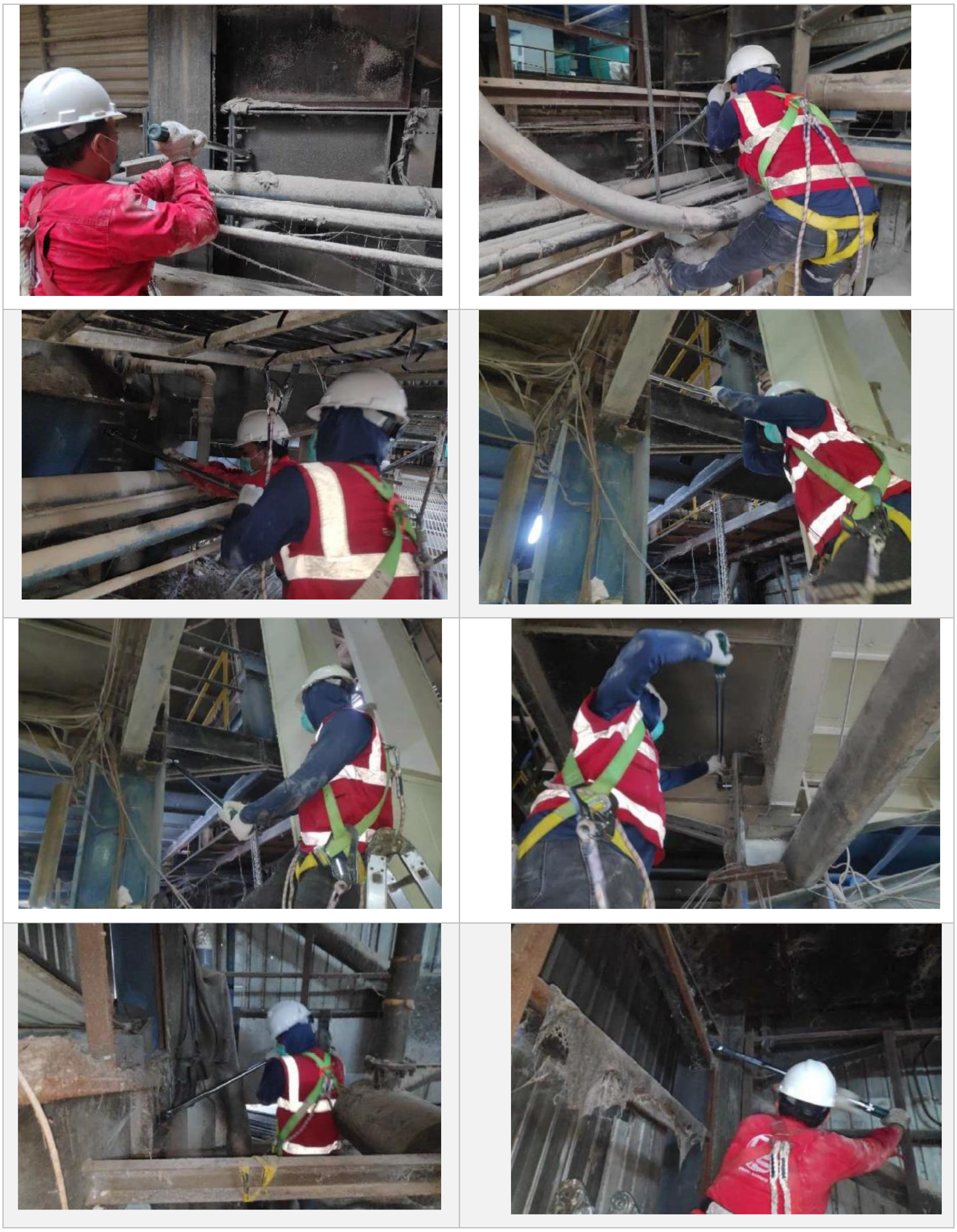


Figure 5. Bolt torque testing (beam and column structure)

In addition to thermal expansion, bolt loosening may also be explained by thermal creep, where prolonged exposure to high temperatures induces plastic deformation in the bolts. Another contributing factor is uneven heat distribution at the joint, which leads to imbalanced tensile forces across bolts in Figure 6. Nevertheless, the retightening process demonstrated that these bolts could still be restored to the required torque values, indicating that their threads and tensile strength were not significantly degraded.

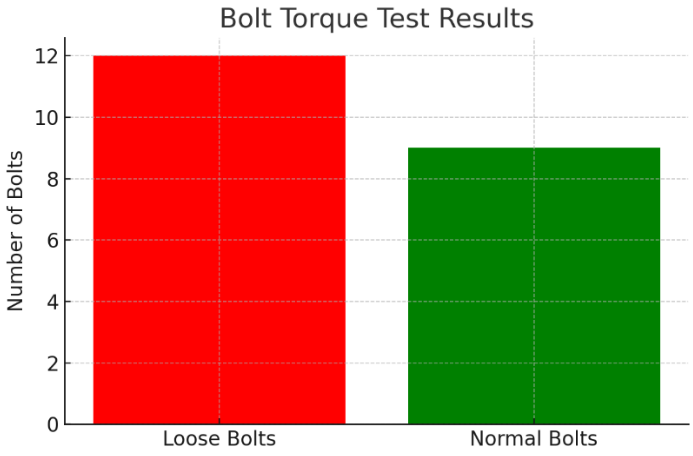
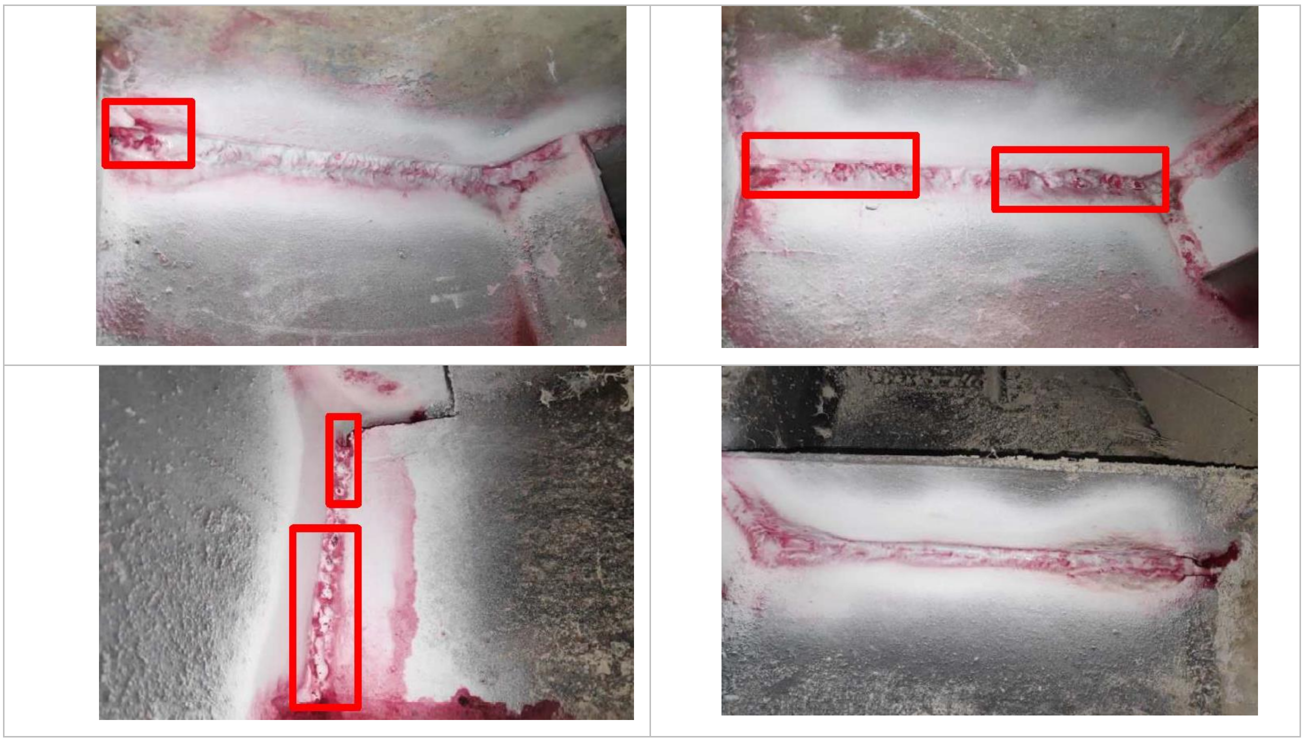


Figure 6. Graph of bolt torque test result (beam and column structure)

The dye penetrant inspection (DPI) results indicated that most weld joints exhibited no relevant defect indications in Figure 7 and Figure 8. Some minor rounded porosity indications (< 5 mm) were detected but remained within the acceptance limits specified in ASME Sec V Article 6. The absence of linear cracks exceeding 1.5 mm strongly suggests that the welds were not severely compromised by fire exposure.

The observed porosity indications can be attributed to two main factors. First, non-uniform cooling following the fire may have induced thermal stresses that generated micro-voids on the weld surface. Second, surface oxidation caused by fire exposure could have influenced defect visibility, although the findings still fell within safe limits. Consequently, the welded joints are considered serviceable, although periodic monitoring is recommended to mitigate the risk of long-term degradation.



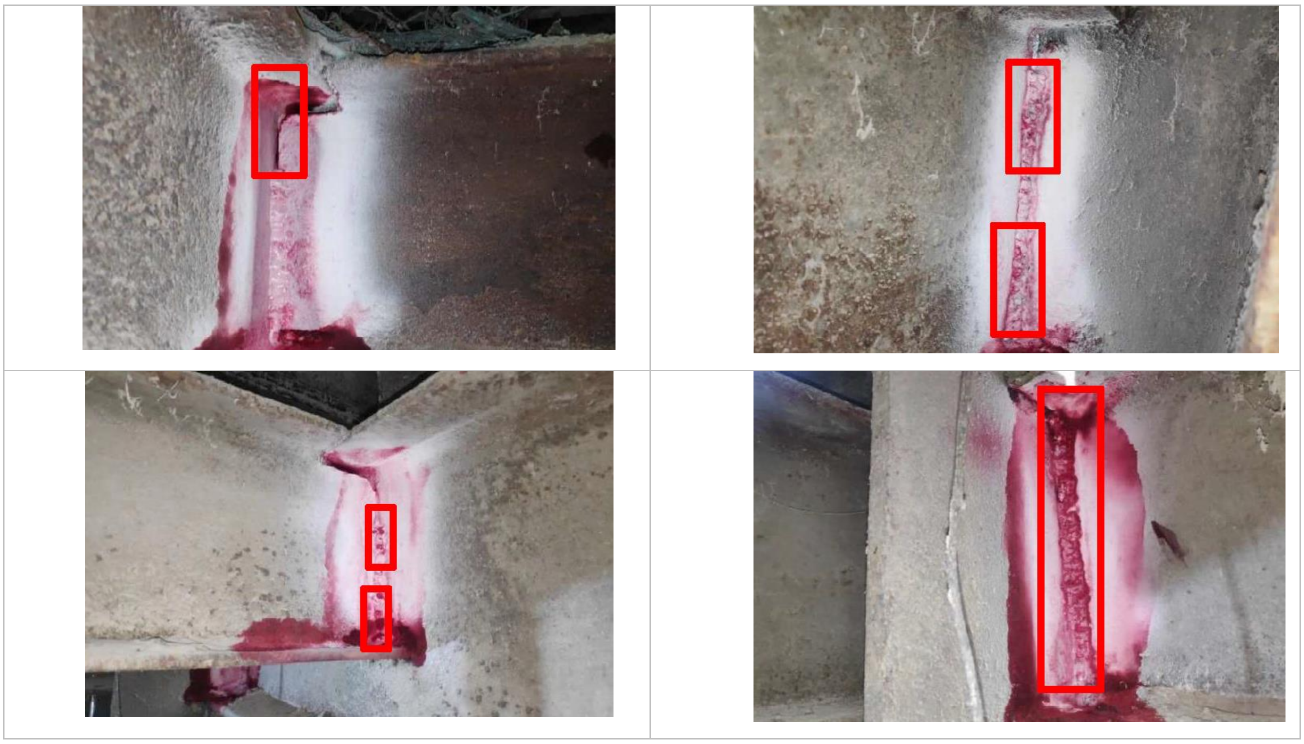


Figure 7. Dye penetrant inspection (beam and column structure)

The test was conducted on 20 weld locations (DP-1 to DP-20). The inspection results showed:

1. Many welds exhibited surface defects exceeding 5 mm in length, such as DP-1, DP-2, DP-3, DP-8, DP-11, DP-12, DP-13, DP-16, DP-17, and DP-18.
2. Several welds were in acceptable condition with no relevant indications, including DP-4, DP-5, DP-7, DP-9, DP-10, DP-14, and DP-19.
3. Cases of incomplete or imperfect welds were identified at DP-6 and DP-20, which represent significant non-conformities in weld quality.

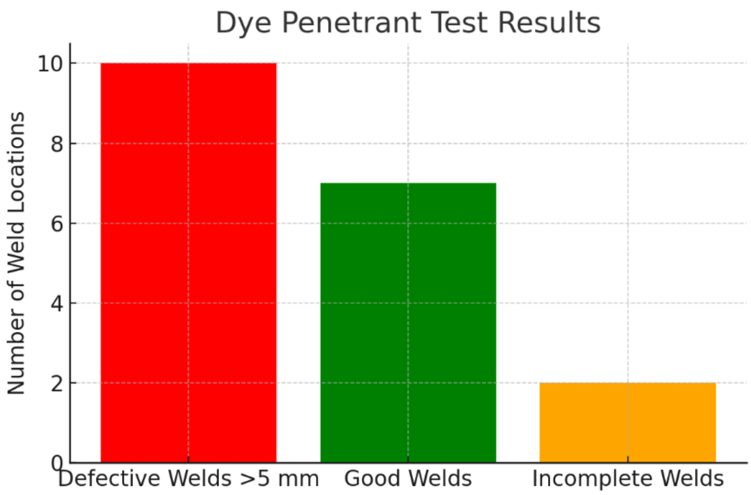


Figure 8. Graph of dye penetrant test result

The combined results of the bolt torque test and DPI provide a comprehensive overview of the condition of steel structural connections after fire exposure. Although some loosened bolts and minor porosity in welds were identified, these conditions remain within safe and acceptable limits. This suggests that the steel tower structure did not experience severe degradation in its connection elements.

Nevertheless, the findings highlight the importance of continuous inspection of fire-exposed steel structures. Loose bolts, even after retightening, may be prone to recurrent relaxation due to load variations or environmental influences. Similarly, small porosity indications in welds may evolve into weak points if left unmonitored. Thus, while the current assessment classifies the structure as "serviceable," a follow-up maintenance program including periodic NDT and visual inspections is strongly recommended.

5. DISCUSSION

The bolt torque test confirmed that although all bolts in the structure remained complete, the loosened condition observed in most bolts reflects the significant impact of fire exposure on mechanical connections. This phenomenon can be attributed to pretension loss due to thermal expansion and stress relaxation. The re-tightening restored torque to standard levels, indicating that bolts can still perform adequately. However, these findings suggest that post-fire bolt connections have increased vulnerability, requiring repeated inspection.

On the other hand, DPI results revealed a more varied condition in welded joints. Many locations showed weld defects exceeding 5 mm, which according to acceptance criteria are considered relevant and require further action. The presence of incomplete or imperfect welds at DP-6 and DP-20 is particularly concerning, as it may significantly reduce joint capacity. Although some welds remained acceptable, the predominance of defect indications highlights a decline in weld quality after the fire, likely caused by thermal stresses, oxidation, or fabrication imperfections.

Taken together, these findings indicate that bolted joints can remain reliable with corrective measures, while welded joints demand more thorough evaluation, local repairs, or even rewelding at critical points. Thus, the overall integrity of the steel tower structure can be maintained, but special attention to welded connections must be prioritized in the post-fire rehabilitation program.

6. CONCLUSION

Based on the field tests conducted on the steel tower structure after the fire, it can be concluded that the conditions of bolted and welded connections showed distinct findings. From the 21 bolts tested with the bolt torque test, all bolts were intact, yet more than half were found loosened, indicating a loss of pretension due to fire exposure. Nevertheless, corrective re-tightening restored torque values to the required standard, confirming that the bolted joints can still function safely.

In contrast, the dye penetrant inspection (DPI) conducted on 20 welded joints revealed that 50% exhibited surface defects exceeding 5 mm, 35% were in acceptable condition, and 10% were identified as incomplete welds. These findings suggest that welded joints are more vulnerable to post-fire deterioration compared to bolted joints and require corrective measures such as local repair or rewelding at critical points.

Overall, the steel tower structure can still be considered serviceable, though special attention must be given to the welded joints along with the implementation of a regular inspection program. The combined application of the bolt torque test and dye penetrant inspection has proven effective in providing a comprehensive assessment of post-fire connection conditions.

7. LIMITATION

This study has several limitations that should be taken into account when interpreting the results. First, the coverage of tested samples was relatively limited, involving only 21 bolted joints and 20 welded joints, which may not fully represent the overall condition of the steel tower. Second, detailed temperature data during the fire event was unavailable, preventing a quantitative correlation between the extent of damage and the actual thermal distribution across structural elements. Third, the applied testing methods were restricted to the bolt torque test and dye penetrant inspection, while other nondestructive techniques such as ultrasonic testing (UT), magnetic particle testing (MT), or hardness testing were not conducted, thereby limiting insights into internal defects and material property changes. Furthermore, this study did not evaluate potential long-term degradation after the fire, including corrosion, cyclic loading effects, or reduction in steel's mechanical performance during its future service life. Finally, the focus of the investigation was mainly on connection elements, whereas primary structural members such as columns and beams were not comprehensively assessed.

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