INTERNATIONAL JOURNAL OF MARITIME TECHNOLOGY

IJMT Vol.15/ Winter 2021 (119-129)

Available online at: www. ijmt.ir

Structural Evaluation of Repair Methods on Dented Tubular Members Used in Jacket Platforms

Seyed Mohammad Hossein Sharifi[1*], Abdolrahim Taheri[2], Ehsan karimipour[3]

*[*1]Assistant Professor, Faculty Member of Mechanical Engineering Department, Petroleum University of Technology, Abadan, Iran; sharifi@put.ac.ir*
[2]Assistant Professor, Faculty Member of Mechanical Engineering Department, Petroleum University of Technology, Abadan, Iran; rahim.taheri@put.ac.ir
[3]MSc. Student in Offshore Structural Engineering, Mechanical Engineering Department, Petroleum University of Technology, Abadan, Iran; E.karimipour@ait.put.ac.ir

ARTICLE INFO

Article History:
Received: 30 Aug. 2021
Accepted: 30 Oct. 2021

Keywords:
Fixed Steel Platforms
Dent Damage
Repair Methods

ABSTRACT

Today, Iran's oil and gas industry requires maintenance, repair, renovation, and reconstruction methods for the existing platforms. It is essential to discuss the repair of offshore platforms since they mostly have been in service beyond their design lives and subjected to damages mentioned in the following. Furthermore, offshore platforms' increased number and service lives add to the need for the in-situ repair of offshore platforms. The most important reasons for the structural repair of offshore platforms include corrosion, fatigue, the collision of floating objects (e.g., vessels), the fall of heavy objects, and intensive storms. By considering the dent damage of platform members, which typically arise from the fall of heavy objects and the collision of floating objects, the present study investigates the damages resulting from such incidents during the operation of platforms and proposes the required repair methods. The repair methods include grouting, member replacement, mechanical clamps, and doubler plates. Once the experimental model of a dent-damaged member was validated, the repair methods were applied to the models, examining the strength of the members. The results indicated that the member strength reduced by up to nearly 40% at a dent depth as large as 0.3 of the member diameter (d=0.3D). However, the reduced strength could be compensated from 12% to about 125%, by applying the repair methods.

1. Introduction

Dent damage is the most common failure cause of fixed steel platforms and can occur in different locations. The collision of a vessel with a platform exposes the upper members of the platform to dent damage. Also, the fall of objects onto the members may subject the entire platform members at different depths within the seawater to dent damages. Dent damage can appear in two general forms: 1) member curvature without dent and 2) local member dent without general curvature. The former occurs in members with a large diameter-to-thickness (D/t) ratio when an object collides near the middle of the aperture, while the latter happens when smaller collisions occur near the end of short-length members with a high D/t ratio. A combination of the two cases can also happen.

For dented-damaged members, codes recommend some simplifications which are not precise and practical for repair actions. API RP 2A has some designing charts to evaluate the thickness required for ship collisions, which are not useable for repair and remedy actions.

Many experimental and numerical studies have been conducted on the dent-damaged tubular steel members of offshore platforms. Smith et al. (1981), Padula et al. (1991), Taby and Moan (1985), MacIntyre (1991), and Duan et al. (1992) studied the residual strengths of dent-damaged tubular members. Ellinas (1984) investigated the ultimate strengths of dent-damaged steel bracing members based on reduced cross-section members to explore the effects of damages. They proposed an analytical equation to estimate the overall residual bucking capacity and local dent damage. They proposed that the ultimate stress corresponding to the residual strength of the dent-damaged member can be obtained by solving a quadratic equation (1) as:

$$\frac{1}{\sigma_e}\sigma_{ud}^2 - \left[1 + \alpha\lambda_d + \frac{A_d e_d}{S_d} + \frac{f_y}{\sigma_e}\right]\sigma_{ud} + f_y + \sigma_{pd}\frac{A_d e_d}{S_d} = 0 \qquad (1)$$

where σ_e is the Euler buckling stress of the intact member, A_d is the reduced cross-section area, S_d is the cross-section elasticity modulus of the dent-damaged area, e_d denotes the eccentricity of the dent-damaged area between the damaged and intact cross-sections, α represents the indirect geometric effects along with the member, λ_d is the column slenderness ratio, f_d is the mean stress of the dent-damaged cross-section, and σ_{pd} Denotes the initial dent plasticity stress. Ricles et al. (1992) studied the residual strength of damaged offshore steel tubular bracing. They applied axial and combined axial-bending loads to six specimens with different D/t ratios. The axial test results revealed a certain decrease in strength. The combined axial-bending loads indicated larger decreases in the strength as compared to the axial loads. Ricles et al. (1993) investigated the grout repair of dent bracing members. They evaluated thirteen experimental specimens with different dent degrees and D/t ratios. A dent as large as 0.15 of the tube diameter was applied. The results revealed a considerable decline in the ultimate strength of the dent-damaged member.

Moreover, the use of grouting interrupted the growth of the dent depth in the connection. It increased the cross-section capacity as compared to the intact member. Paik et al. (2003) studied the ultimate strength of dent-damaged steel plates under axial-compressive loads using ANSYS. They investigated the effects of the shape, dent size, and dent location on the ultimate strength with hinged supports on both sides of the plate. Parsanejad (1987) studied the effects of grouting on the strengths of damaged members. They proposed an equation for the parameters and the effect of grouting on the ultimate strength of the damaged member by investigating ten small-sized experimental models and parametrically evaluating the results. Ueda et al. (1985) examined the behavior of dent-damaged tubular members. They studied the strength of a numerical model member under axial and bending loads. The findings demonstrated good agreement between the experimental and numerical results. Mugahed Amran et al. (2018) studied the properties and applications of fiber-reinforced polymer (FRP) in strengthening RC structures. They reviewed the FRP design, serviceability performance, matrix, applications, and material properties.

FRP composites were accepted as a mainstream construction material for repair, strengthening and retrofit of concrete structures. Rehabilitation function is mainly influenced by the direction of polymers fibers used. FRP composite is highly resistant to chloride ion and chemical attack compared to steel bars. Nassiraei and Rezadoost (2020) investigated the stress concentration factors in tubular T/Y-joints strengthened with FRP subjected to compressive load in offshore structures. The effect of FRP layers and joint geometry on the SCFs and the SCF ratio of the reinforced to the unreinforced joints were investigated through a parametric study. Results showed that the SCF of an FRP-reinforced T/Y-joint can be down to 34% of the SCF of the corresponding unreinforced joint. Also, two parametric formulas were proposed for determining the SCFs in T/Y-joints reinforced with FRP. Nassiraei (2019, 2019, and 2021) also has conducted three more research in this area by evaluating the static strength of tubular T/Y-joints reinforced with collar plates at fire-induced elevated temperature, the static capacity of tubular X-joints reinforced with fiber-reinforced polymer subjected to compressive load, and static capacity of collar plate reinforced tubular X-connections subjected to compressive loading: the study of geometrical effects and parametric formulation.

Arean et al. (2017) studied a framework to assess the structural integrity of aging offshore jacket structures for life extension. They provided recommendations for simulating structural degradation, loading history, and fatigue strength for corroded details. Effect of localized corrosion on SCF's, new fatigue damage theory, and guidelines for strengthening/inspection are included. A case study on an aged jacket structure highlights the applicability, significance, and validity of the framework. Bruin (1995) investigated the residual strength and repair of offshore platform bracing members by examining dents and D/r ratios. They subjected intact models to axial loads by a mandrel and then applied a lateral axial load to the member. The grouting of the member was proposed as a repair method. Also, the experimental results were compared to the numerical ones. The present study employed the model Bruin (1995) proposed to validate the dent-damaged models and examine the strength reduction of dent damages. Also, the strengths of the members were evaluated by applying the common platform repair methods.

In this paper, considering conducted researches so far, there is a lack of comparison between repair actions. It is required to determine the efficiency and strength of each repair method in comparison to other methods. The paper evaluates the ultimate strength of doubler plates, grouting, mechanical clamps, and member replacement individually, and next a comparison between the strength have been provided to help the engineers to reach a consensus in selecting proper repair action.

2. Modeling

The present study validated the experimental model of Bruin (1995) as the damage in question. The dent damage characteristics are the effective dent diameter and length. Two dent-damaged specimens with dent depths as large as 0.15 and 0.3 of the member diameter were employed. The effective dent length was incorporated, according to Bruin (1995). This length is the length of the dent induced to each member in a damaged state. Table 1 describes the specimens. In this table, d parameter stands for dent depth, L is member length, L_{eff} is effective dent length, t is the thickness of the member, D is member diameter, λ is slenderness ratio, P_n is the nominal buckling strength, and P_y is the ultimate strength of the member under buckling. Dent damages have been modeled with SOLIDWORKS software. The dent was modeled using splines in the longitudinal direction to model the deformation-induced to the members. ABAQUS was used to simulate the FEM of dent-damaged members. Numerical approaches are commonly adopted to solve engineering problems. Once the geometries of the dent-damaged members were constructed, the steel properties were defined according to the ASTM A572 Standard (2018). The highly executable grout of Ducorit is produced by Illinois Tool Works Inc. (ITW) was exploited. Tables 2 represent the steel and grout properties. Fig. 1 illustrates the two experimental damage models. Modeling is conducted using solid elements. Meshes in all models considered to be C3D8R and the mesh size through-thickness was considered to be 2 in some cases 3 elements to apply the solid behavior of the member to the models. More refined meshing have considered for dented areas and mesh sizes have been tested multiple times to reach the best fit for the experiment results. Axial forces have been subjected to the models to avoid the complexity of the comparison among remedy actions. Subjected forces to the models are displacements which is subjected to the support of the model.

3. Validation of the experimental models

The results reported by Bruin (1995) were compared to the load-displacement results obtained in ABAQUS to validate the models. The comparisons indicated good agreement between the experimental and numerical load-displacement results, as shown in Figs. 2 and 3. In order to validate the intact modeling, intact member has been modeled by ABAQUS Software and the ultimate strength has been verified using formulations of ASCE code on tubular members, which is reliable.

Static loads were applied to extract the local pushover graph of the member by controlling the displacement. The elastic stiffness of the charts is different because of the different properties of the sections. Hinged joints were applied to the ends of the tubes as the boundary conditions. The hinge boundary condition was defined by coupling the member cross-section at the center of the member. Different mesh sizes were examined. Since a change in the meshes did not influence the output, the sensitivity analysis of the meshes was excluded from the results.

4. Results of the repair methods

Once the experimental models were validated and showed good agreement with the numerical models, the repair methods of grouting, member replacement, mechanical clamps, and doubler plates were applied, investigating the member strength for each of the methods. Many factors determine a member repair method. The selection of the ideal repair method depends on the time, equipment, damage location, and damage level. The present study aimed to compare the strength obtained by applying member replacement, doubler plates, mechanical clamps, and grouting to the damaged area and the improvement of the member. The repair methods are described in the following, providing the results.

4.1. Member replacement

In this method, the dent-damaged members are replaced with intact members. Figs. 4 and 5 compare the intact and dent-damaged members. For specimen 1 with a dent of 0.15 of the diameter, the member's strength was reduced by up to nearly 15%. According to Fig. 5, the strength of specimen 2 with a dent damage depth as large as 0.3 of the diameters was reduced by up to approximately 35%.

4.2. Doubler plates

This repair method employs a plate of the same material as the base member to fill the dented area. The thickness of the doubler plate is typically smaller than or equal to that of the main plate. To repair the dent-damaged member, a plate with a width of 344 mm, a length of 1600 mm, and a thickness equal to the member thickness was applied at different base member thicknesses and the same curvature as that of the member. The doubler plate was intended to cover the entire dented area. Fig. 6 demonstrates the model and meshing. The material of the member was applied to the doubler plate. The doubler plate was tied by 10 mm to serve as the joint of the doubler and base plates. The modeling of the plate with a thickness twice as large as that of the base member indicated that a rise in the thickness did not affect the bucking capacity improvement of the member.

Figs. 7 and 8 compare the stiffness curves of the intact, dent-damaged, and doubler plate-repaired members for specimens 1 and 2, respectively. As can be seen, the doubler plate repair increased the bearing capacity as compared to the dent-damaged member. According to Fig. 7, the bearing capacity increased by 12%. Since the damage of specimen 2 was greater than that of specimen 1, the doubler plate improved the strength by 24%, as shown in Fig. 8.

4.3. Mechanical clamps

A mechanical joint is a connection between two concentric tubular members, in which the inner member is completely circular. In contrast, the outer member is composed of two or more saddles tightened on the inner member by long stud bolts. Fig. 9 illustrates the clamp modeled for the repair of the dent member. Figs. 10 and 11 compare the results of the intact, dent, and clamp-repaired members for specimens 1 and 2, respectively. As can be seen, the mechanical clam repair improved the bearing capacities of specimens 1 and 2 by 9.04% and 22.27%, respectively, as compared to the dent member. It is evident that the mechanical clamp repair of the members improved the bearing capacities of the members to a level near that of the intact members, and the repaired members showed similar behavior to the intact ones.

4.4. Grouting

To apply grout repair, a cross-section with a diameter as large as the inner diameter of the member and a length as large as the dent curvature was modeled. The grout material was that of the grout mentioned above. Fig. 12 depicts the grout-repaired member model. Tangent contact with perfect friction and normal stiffness was applied to the grout-member connection. Figs. 13 and 14 compare the load-displacement curves of the intact, dent, and grout-repaired members for specimens 1 and 2. As can be seen, grouting improved bearing capacity. The grout repair increased the bearing capacity beyond the intact member for both specimens; however, grouting would increase the weight of the platform.

4.5. The capacity comparison of the proposed repair methods

The proposed repair methods were compared by equation 2.

$$E = \frac{F_{repaired} - F_{damaged}}{F_{damaged}} \times 100 \qquad (2)$$

Where E is the ratio of the capacity of the repaired member to that of the damaged member, tables 4 and 5 compare the repair methods in the improvement of the damaged member. As can be seen, grouting was found to be the most optimal strength improvement method.

5. Conclusion

The present study investigated the dent-damaged members of fixed steel platforms and their strengthening methods by applying different repair methods. The modeled dent member was extracted by validating the experimental model of Bruin (1995). The strength of the dent-damaged member was obtained. Two specimens with dent depths as large as 0.15 and 0.3 of the member diameter were modeled, showing 13% and 26% strength reductions, respectively.

The repair methods of member replacement, doubler plates, mechanical clamps, and grouting were applied. The use of the doubler plate enhanced the strengths of the dent specimens with the larger and smaller dent depths by 24% and 12%, respectively. The mechanical clamp repair improved the strength of the dent member to that of the intact member. Furthermore, the use of grouting as the repair method significantly enhanced the strength and stiffness of the member (125%). The bearing capacity of the repaired member was reported to be about twice as large as that of the intact member.

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Table 1. The specifications of the experimental models

	Specimen	L (mm)	L_{eff} (mm)	t (mm)	D (mm)	d/D	λ	$\lambda_{AISC\ Code}$	P_n (kN)
Experimental data	1	4518.15	1355.45	6.43	219.38	0.15	34.14	93.07	2158.70
	2	4546.6	1363.98	4.8	218.9	0.3	46	88.17	2263.67

Table 2. Material properties

Material	E (Mpa)	*v*	Density (kg/m^3)	F_y (Mpa)	Strain Hardening Rate
Steel	210000	0.3	7850	345	2.5%
Grout (Ducorit D4)	70000	0.19	2740	Fc: 200,000	-
				Ft: 10,000	

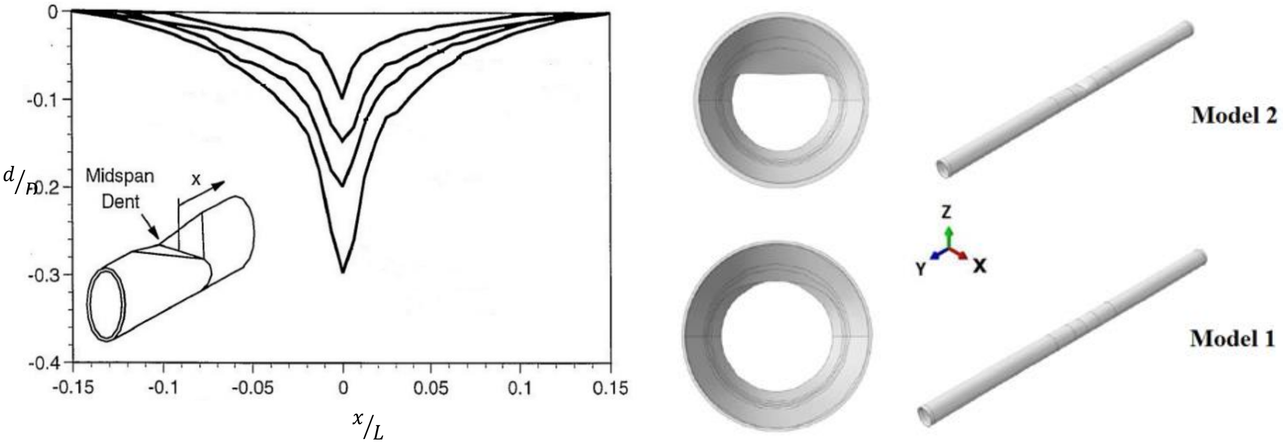


Fig. 1. The dent models.

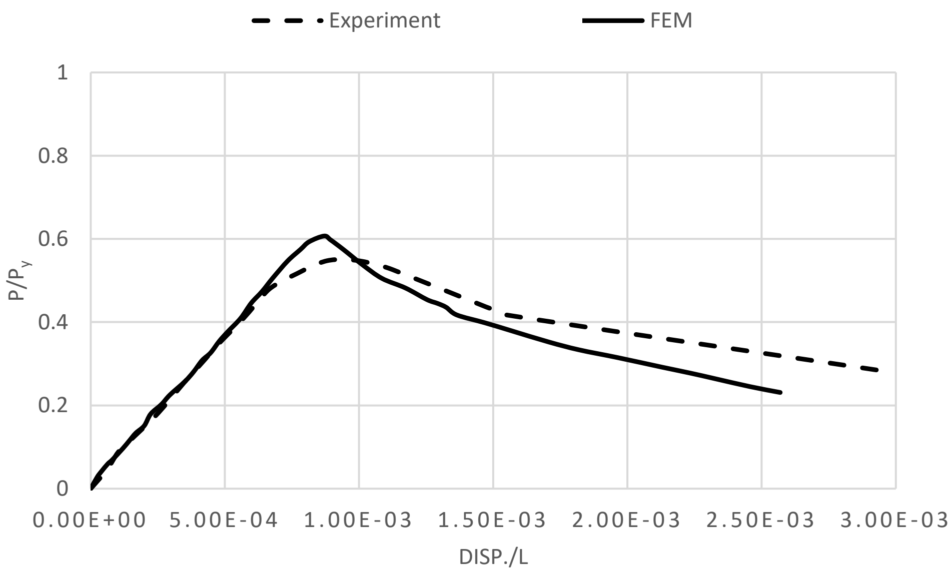


Fig. 2. A load-displacement curve comparison of the experimental and numerical models for specimen 1 (d=0.15D).

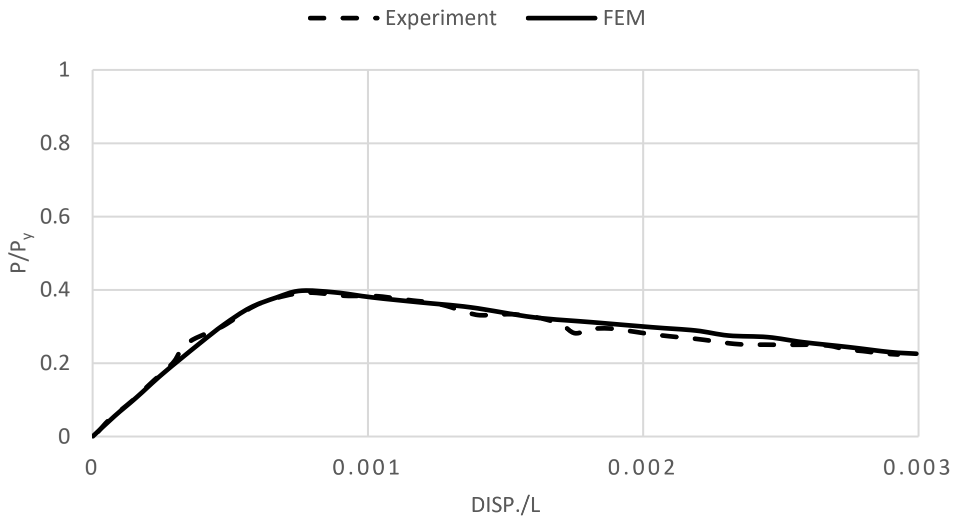


Fig. 3. A load-displacement curve comparison of the experimental and numerical models for specimen 2 (d=0.3D).

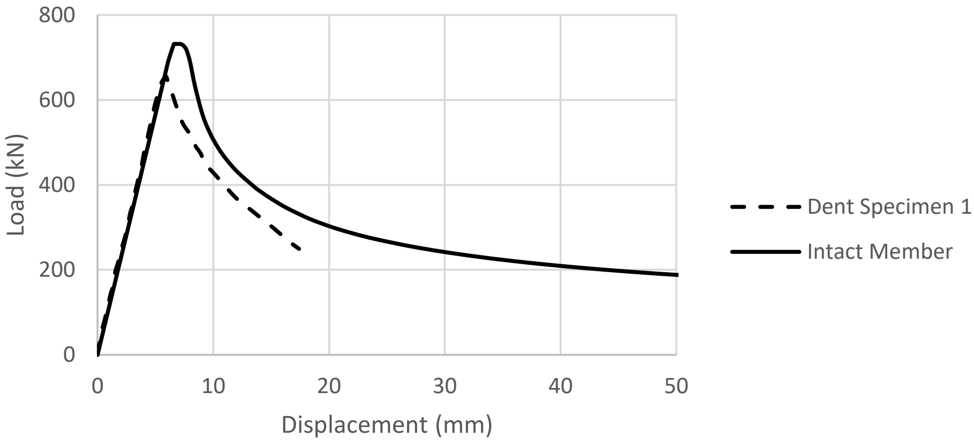


Fig. 4. A load-displacement curve comparison of the replaced and dent members for specimen 1 (d=0.15D).

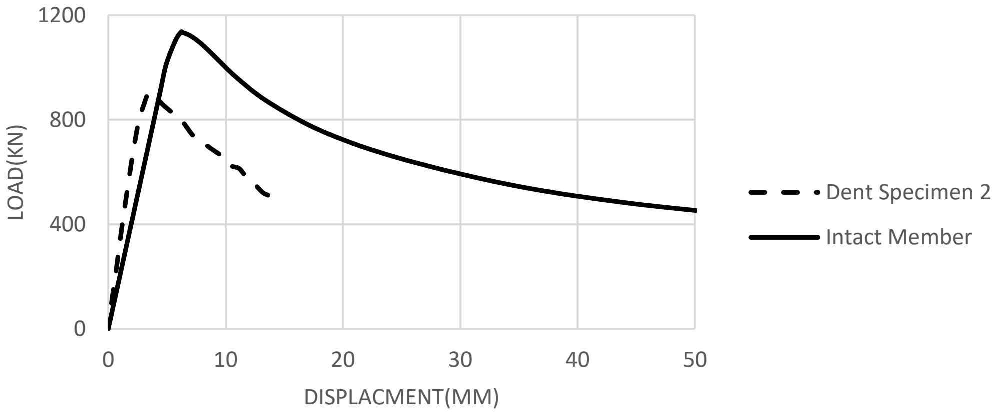


Fig. 5. A load-displacement curve comparison of the replaced and dent members for specimen 2 (d=0.3D).

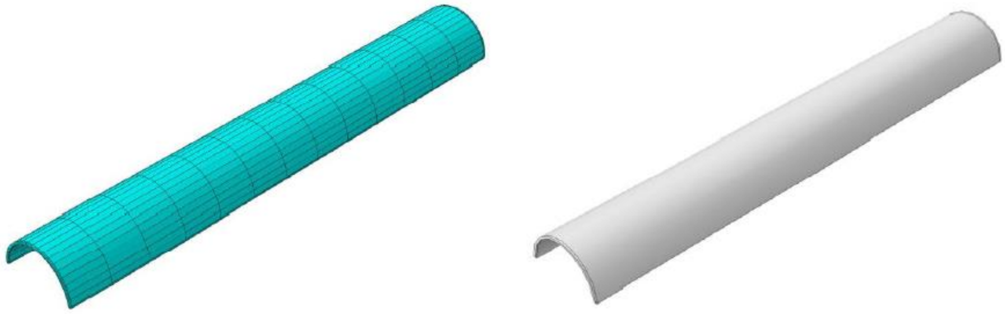


Fig. 6. The doubler plate model for dent repair

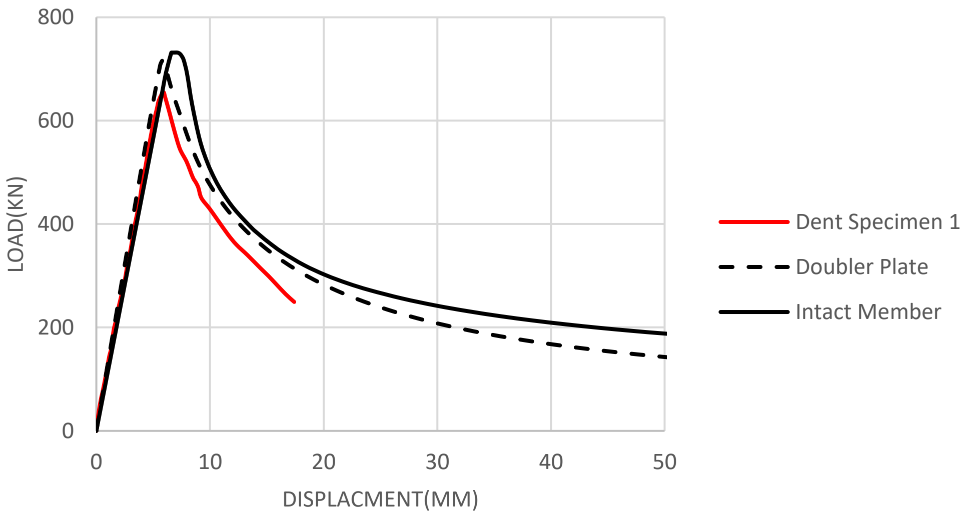


Fig. 7. A load-displacement curve comparison of the intact, dent-damaged, and doubler plate-repaired members for specimen 1 (d=0.15D).

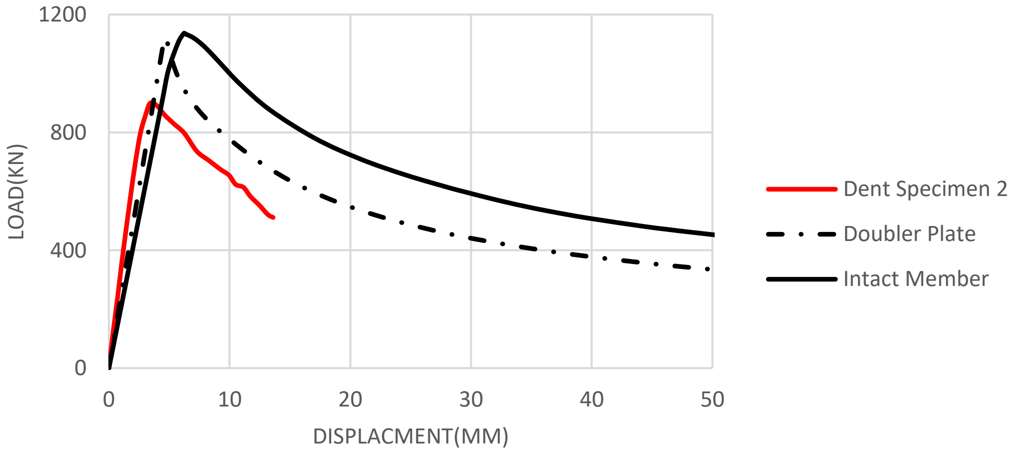


Fig. 8. A load-displacement curve comparison of the intact, dent-damaged, and doubler plate-repaired members for specimen 2 (d=0.3D).

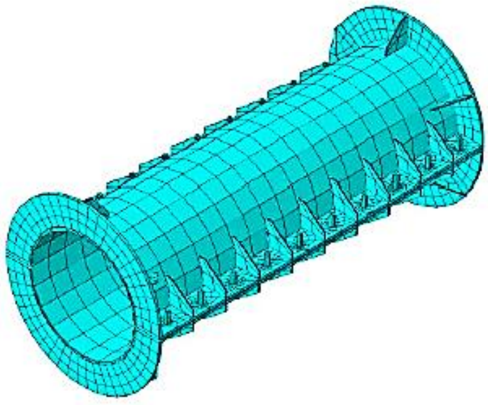


Fig. 9. The modeled clamp

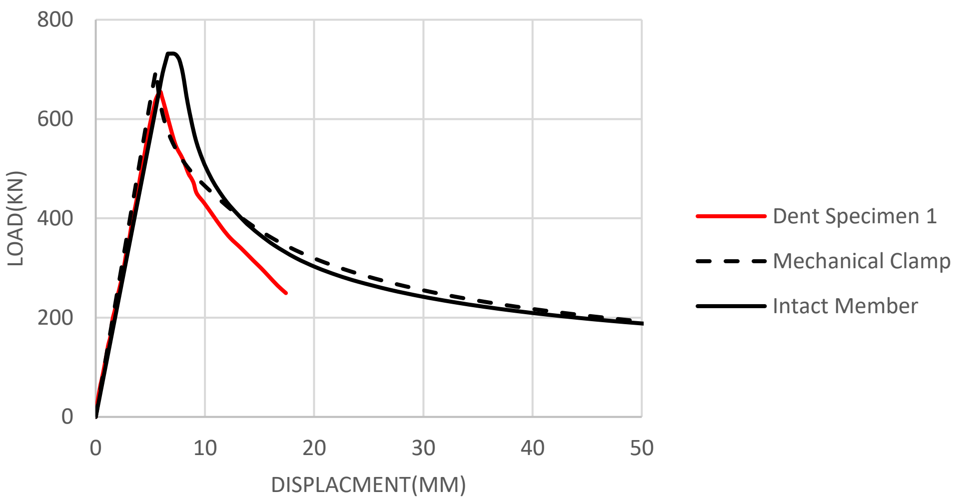


Fig. 10. A load-displacement curve comparison of the intact, dent-damaged, and mechanical clamp-repaired members for specimen 1 (d=0.15D).

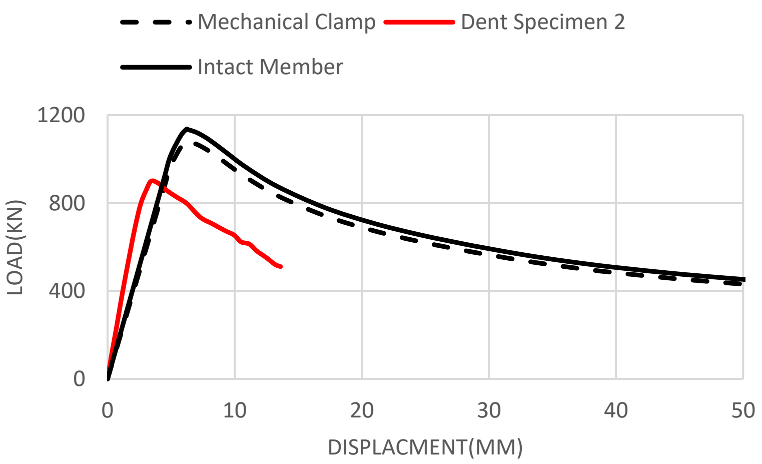
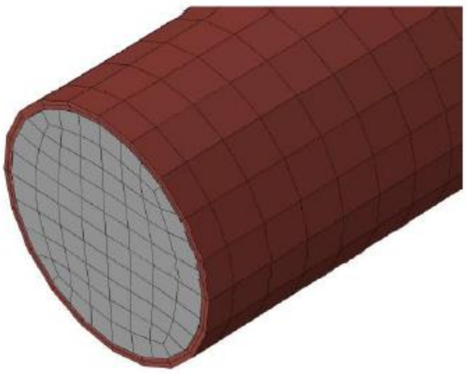


Fig. 11. A load-displacement curve comparison of the intact, dent-damaged, and mechanical clamp-repaired members for specimen 2 (d=0.3D).



Fig, 12. Grout repair meshing

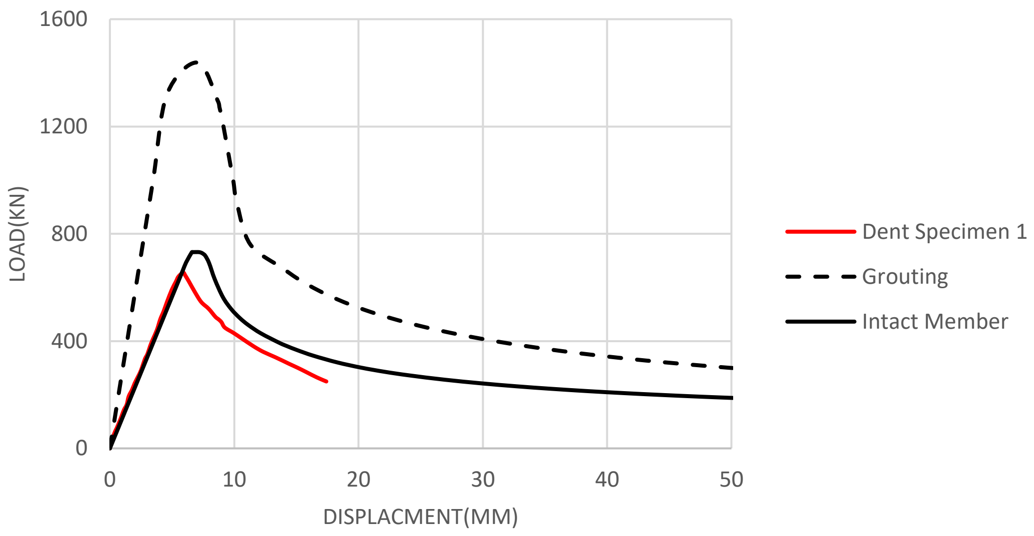


Fig. 13. A load-displacement curve comparison of the intact, dent-damaged, and grout-repaired members for specimen 1 (d=0.15D).

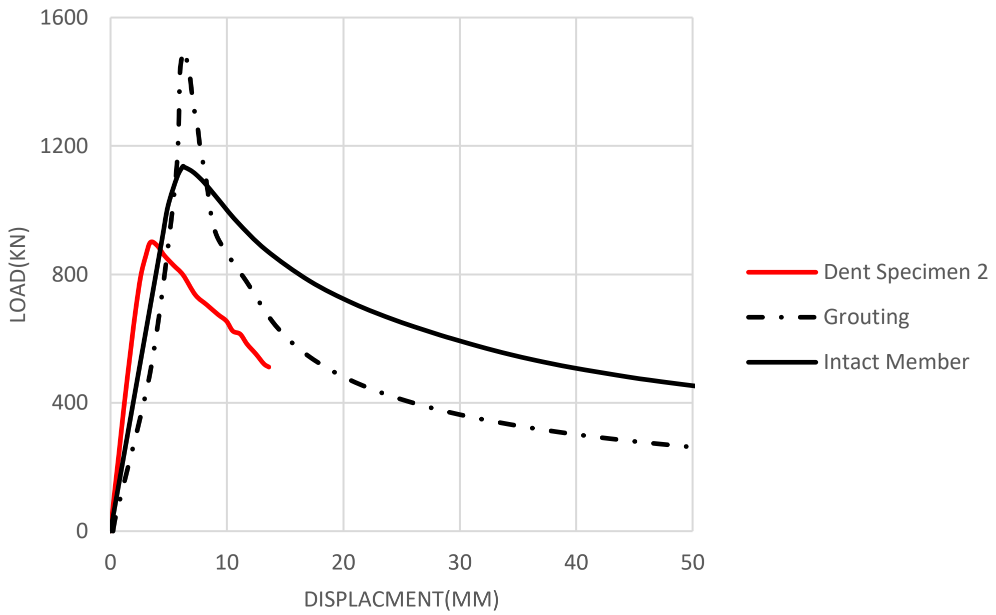


Fig. 14. A load-displacement curve comparison of the intact, dent-damaged, and grout-repaired members for specimen 2 (d=0.3D).

Table 4. A dent damage improvement comparison of the repair methods for specimen 1 (d=0.15D).

Specimen	Disp. (mm)	Load (kN)	E (%)
Dent	5.5153	640.29	0.00
Doubler plate	5.8093	716.21	11.86
Mechanical clamp	5.5427	698.15	9.04
Grouting	7.0709	1438.40	124.65
Member Replacement	7.0789	731.85	14.30

Table 5. A dent damage improvement comparison of the repair methods for specimen 2 (d=0.3D).

Specimen	Disp. (mm)	Load (kN)	E (%)
Dent	3.4279	899.75	0
Doubler plate	4.7093	1121.82	24.68
Mechanical clamp	6.2129	1082.08	20.27
Grouting	5.6959	1758.41	95.43
Member Replacement	6.2129	1136.18	26.24

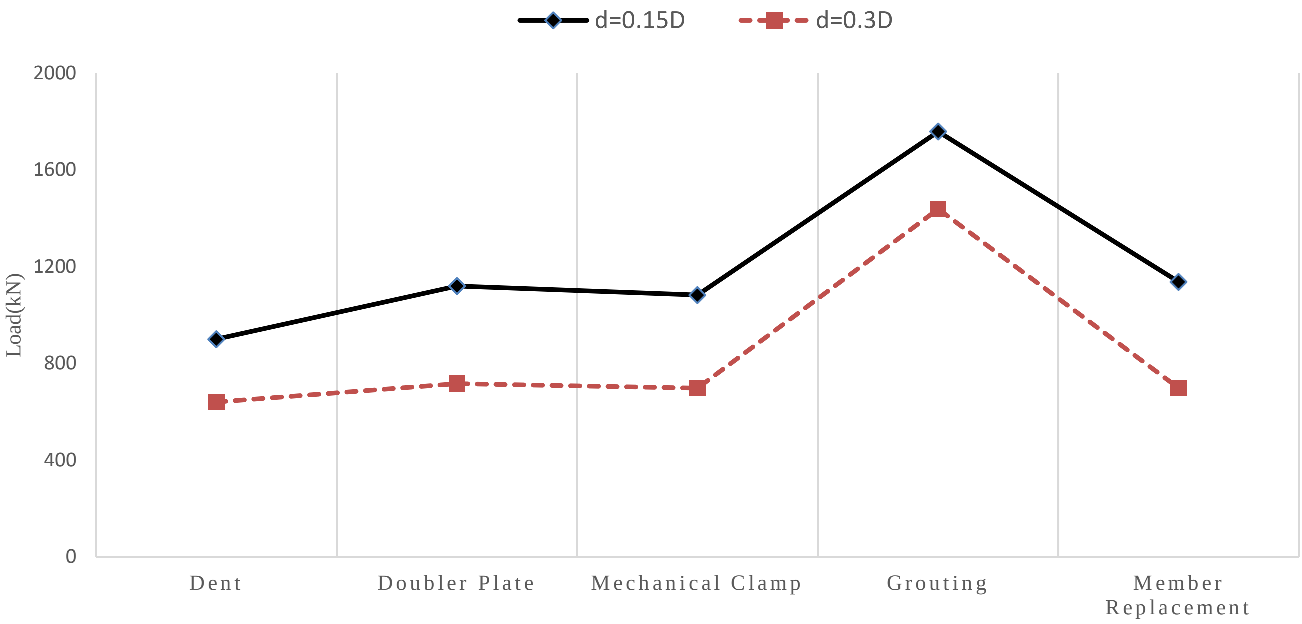


Fig. 15. A dent damage improvement comparison of the repair methods for both specimen