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Comparison of Concrete and Steel Jacket Methods for Reinforcing A Concrete Bridge Pier by Numerical and Experimental Studies

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Abstract

Various rehabilitation and strengthening procedures have been developed in recent decades. A study to determine which methods can be implemented to increase the useful life of the bridge before strengthening must be performed. In this study, the seismic behavior of a reinforced concrete bridge pier with dimension 3.5 × 3.5 m, which was reinforced by two steel and a concrete jacket, was investigated. Nonlinear geometric models and materials were analyzed to estimate the seismic parameters of the pier. Results show an increase in energy absorption, ultimate strength, and ductility for the steel jacket, as well as a greater increase in the concrete jacket. Using a box concrete jacket with a dimension of 3.5 × 3.5 m, the increase in percentages of energy absorption, ultimate strength, and ductility were 38, 14, and 13, respectively. Therefore, the concrete jacket enhances the mentioned parameters.

Abstrak

Perbandingan Metode Jaket Beton Dan Baja Untuk Memperkuat Suatu Dermaga Jembatan Beton Melalui Kajian Numerik Dan Eksperimen. Berbagai prosedur rehabilitasi dan penguatan telah dikembangkan dalam dekade-dekade belakangan ini. Suatu kajian untuk menentukan metode yang mana yang dapat diimplementasikan untuk meningkatkan usia pakai jembatan sebelum penguatan harus dilakukan. Di dalam kajian ini, perilaku seismik suatu dermaga jembatan beton bertulang dengan dimensi 3,5 × 3,5 m, yang diperkokoh dengan dua jaket baja dan beton, diinvestigasi. Model-model geometri non linier dan bahan-bahan dianalisis untuk mengestimasikan parameter-parameter seismik dermaga. Hasil-hasilnya menunjukkan suatu peningkatan penyerapan energi, kekuatan akhir, dan kekenyalan jaket baja, dan juga peningkatan yang lebih besar pada jaket beton. Dengan menggunakan suatu jaket beton kotak dengan dimensi 3,5 × 3,5 m, kenaikan persentase penyerapan energi, kekuatan akhir, dan kekenyalan masing-masing adalah 38, 14, dan 13. Dengan demikian, jaket beton meningkatkan parameter-parameter yang telah disebutkan.

Keywords: concrete jacket, ductility, energy absorption, steel jacket, strengthening, ultimate strength

1. Introduction

Information gathering and analysis are the most significant parts of any research. Therefore, it is very important to determine the method or methods that can analyze and report the characteristics of the gathered information [1]. The damage to a column by an earthquake may have serious consequences; specifically, the destruction of a column puts people on or under it at risk. In addition, the column should be replaced or a new solution be defined after the earthquake. Elimination of a column, even temporarily, has consequences because the columns are vital arteries of transportation systems. After critical earthquake conditions, column elimination creates a defect in its emergency performance. In recent years, different numerical models, such as finite element, finite difference, and discrete element, have been used to analyze columns; currently, nearly all are analyzed numerically. The finite element method is very appropriate for column modeling. In this scientific method, the research procedure, goal, nature and its procedure, measuring and gathering instrument, and analysis and deduction are explained [2].

In 2020, Li *et al.* [3] presented an experimental and numerical study on the impact process, damage and failure mode, dynamic behavior, and impact resistance of reinforced concrete (RC) piers under lateral impact loading. Using a horizontal impact system, a series of simplified truck model collision tests on the square sectional RC piers were performed, in which two main design parameters, i.e., impact velocity and the longitudinal reinforcement ratio, were evaluated. Moreover, detailed finite element models were established by the commercial program LS-DYNA, which are verified against the test results. The shape of the impact force time-history does not exhibit the platform stage of conventional drop hammer impact tests, which is attributed to the shear failure mode in the present columns. The damage level, impact force, displacement at impact position, and energy dissipation increased with increasing impact velocity. In addition, increasing the longitudinal reinforcement ratio effectively improved the impact resistance of RC piers; a plastic hinge forms with the hoop reinforcement, yielding before the shear failure of column. Finally, the impact force causes a considerable change to the axial force on RC piers during the impact process.

In 2020, Wakjira *et al*. [4] proposed a fractional factorial design model for seismic performance of RC bridge piers retrofitted with steel-reinforced polymer (SRP) composites. They explored the effects of key design parameters on the performance of seismically deficient rectangular cross-section RC bridge piers strengthened with SRP composites. The nonlinear response of the bridge piers was modeled using fiber-based section discretization. Three-level fractional factorial design of the experiments at a 5% significance level was used to capture the effects of design parameters and their interactions, including concrete compressive strength, the yield strength of the steel bars, geometric ratio of the longitudinal bars, internal transverse reinforcement spacing, pier aspect ratio, and number of retrofitting SRP layers.

In 2020, Li *et al*. [5] assessed vehicular impact resistance of seismic-designed RC bridge piers. First, they designed four typical double-pier RC bridges based on the Chinese seismic design specifications considering different seismic hazard levels, and they established the corresponding refined finite element models using LS-DYNA. Based on the validated material models and numerical algorithm, the numerical simulations of total 108 vehicle-pier collision scenarios were systemically performed, including a light pick-up truck, medium Ford 800 truck, and heavy tractor-trailer truck with different tonnages of 3–30 t and collision velocities of 40–120 km/h. The pier's deformation and vehicular impact force results indicated that the bridge pier designed with enhanced seismic capacity exhibits a lower damage level, survives the higher impact speed of a heavy truck, and withstands successive cargo impact.

In this study, the seismic behavior of a RC bridge pier with a dimension of 3.5 × 3.5 m and bar network retrofitted by steel and concrete jacket was evaluated using nonlinear geometric models and materials.

2. Numerical Simulation

According to the reliability of the simulation performed in the previous chapter, a comparison of the seismic behavior of RC concrete columns with steel jacket-reinforced and concrete jacket-reinforced concrete column was conducted. In this paper, the unit of length and force were meter and Newton, respectively, and a normal column was retrofitted using two methods. The first strengthening method was based on a steel jacket and the second strengthening method was a concrete jacket with a dimension of 3 × 3.5 m and height of 6 m. A nonlinear static analysis method with displacement control was implemented. In this research, the volumetric (3D) finite element was used for concrete, longitudinal bar, and stirrups definitions. For definition of the concrete materials, Figures 1 and 2 were used for compression and tensile behavior of the concrete, respectively.

The required numerical values of the concrete material under compression and tensile are defined in Table 1.

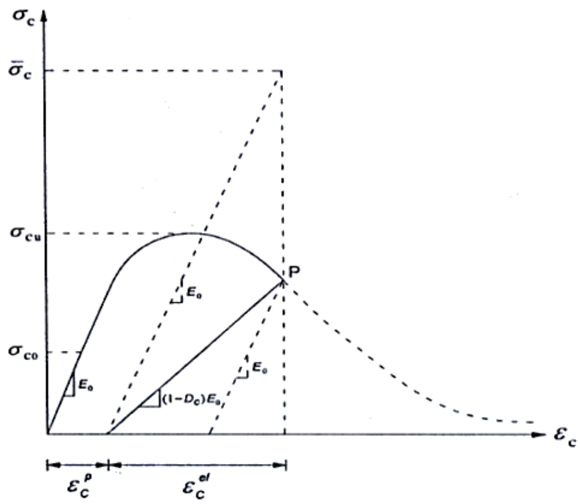

Figure 1. Strenth Curve of Concrete Compression Bahavior [6]

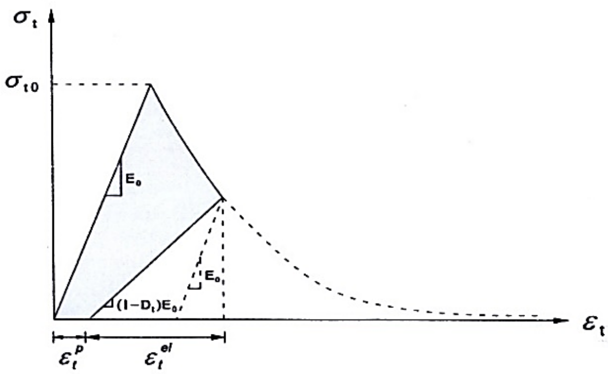

Figure 2. Strenth Curve Of The Concrete Tensile Bahavior [7],[8]

Steel jacket-reinforced and concrete jacket-reinforced samples were studied for full consideration of the system performance because of strengthening using bar implantation method. The specifications are presented in Table 2. Figure 3 shows the jacket-reinforcing and bar implementation methods in the ABAQUS Ver. 6.12 [9] software. The modeling was three-dimensional and the concrete column was a solid part, and the rebar and braces were wire elements.

Table 1. Behavior of Concrete in Tension and Pressure According to Figures 1 and 2

Compressive Strength		Tensile Strength	
Strain (m)	**Tension (N/mm^2)**	**Strai (m)**	**Tension (N/mm^2)**
0.00000	20972037.3	0	15000000.00
0.00082	24525632.5	0.00082	16650000.00
0.00119	26215046.6	0.0063	12300000.00
0.00274	29186085.2	0.0177	6040000.00
0.00407	31038615.2	0.022	4540000.00

Table 2. The Specifications of the Research Models

Strengthening Mode	Column Height (M)	Model Number
Unreinforced	10	M-1
Steel jacket-reinforced	10	M-2
Concrete jacket-reinforced	10	M-3

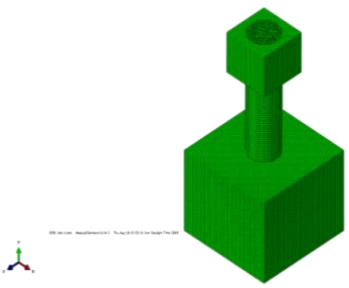

Figure 3. Modeling Jacket-reinforcing and Bar Implementation Methods in the ABAQUS Software

For rebar, the steel material is specified as elastic–plastic. The concrete was modeled as "Concrete Damaged Plasticity." This behavioral model receives the tensile and compressive stresses of the concrete separately. The rebar are intended to be buried in the concrete. The boundary condition for the lower rigid plate was fixed and the boundary condition for the upper rigid plate was in the vertical direction to apply a compressive load to the concrete column. For each part, proper meshing was needed to provide suitable results [10],[11].

The results of the M-1 model. In this step, the calculation of existent tensions in the structural elements was performed according to Table 3 using ABAQUS software outputs. The existing tension in the concrete was greater than the cracking module of the concrete, which was 3.52 MPa according to the $0.6\sqrt{f'_c}$ relationship. Therefore, cracking was observed at the critical points of the column base, which was the base of the bridge. In addition, yield occurred in the bars because of the tensile according to the existent tensions in bars. The load–displacement curve for the M-1 model and results are is presented in Figure 4 and Table 3, respectively. The onset yield in the M-1 model is shown in Figure 5. Figure 6 presents the sequence yield of the M-1 model, and Figure 8 shows the created tension in the longitudinal and transverse bars of the foundation in the M-1 model.

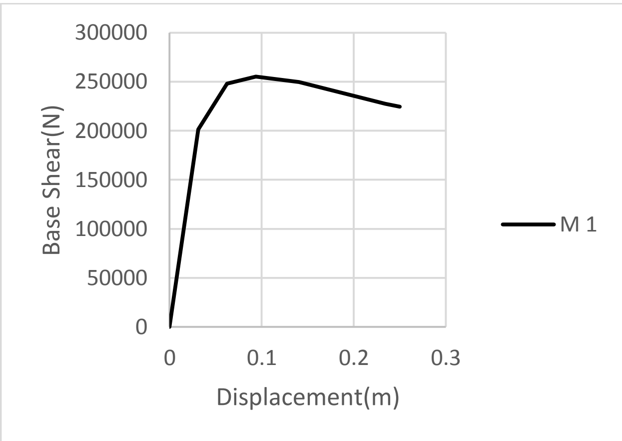

Figure 4. Load–displacement Curve of M-1

Table 3. The Results of the M-1 Model

Ultimate Strength (kN)	Energy Absorption	Yield Displacement (m)	Ductility	Model Name
255	53.14	0.0307	8.14	M-1

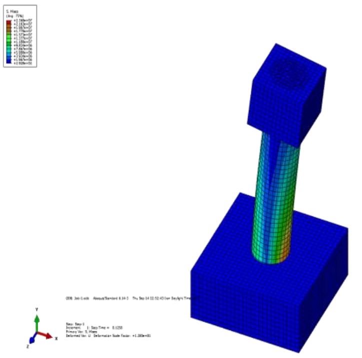

Figure 5. Onset Yield in the M-1 Model

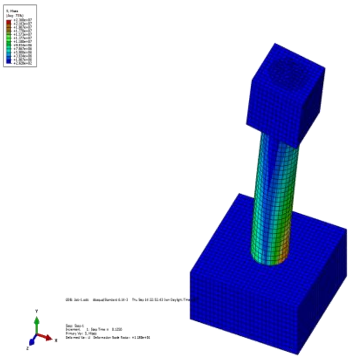

Figure 6. The Sequence Yield in the M-1 Model

Table 4. The Magnitude of Tension in M-1 Members During Failure

Maximum Tension in Concrete	Model Name
46 MPa	M-1

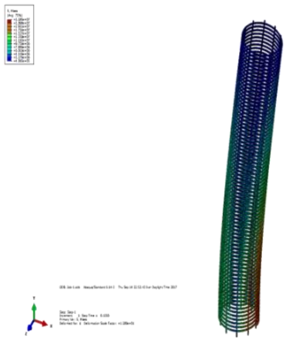

Figure 7. Created Tension in the Longitudinal and Transverse Bars in the M-1 Model

Results of the M-2 model. In this step, the calculation of existing tension in structure members was performed according to the software results. The concrete tension was greater than the cracking module obtained from the $0.6\sqrt{f'_c}$ of value 3.52 MPa. Therefore, cracking at the critical points of the column base, which is a bridge pier, was observed. However, the amount of existing tension of the concrete in this model decreased 11% because of steel jacket application as observed in the overall pressure on the concrete. The load–displacement curve for the M-2 model is presented in Figure 9 and the onset yield is shown in Figure 10. Figure 11 presents the sequence yield of the M-2 model. The amount of tension in the members is presented in Table 6. Figure 12 shows the created tension in the longitudinal and transverse bars of the foundation in M-2 model and the created tension in the longitudinal and transverse bars of the foundation are illustrated in Figure 13 for model M-2.

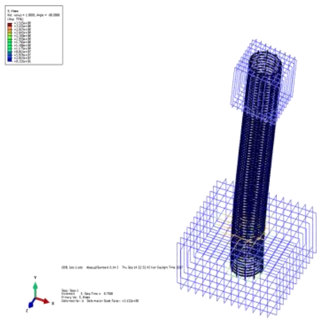

Figure 8. Created tension in the longitudinal nad transverse bars of the fundation in the M-1 model

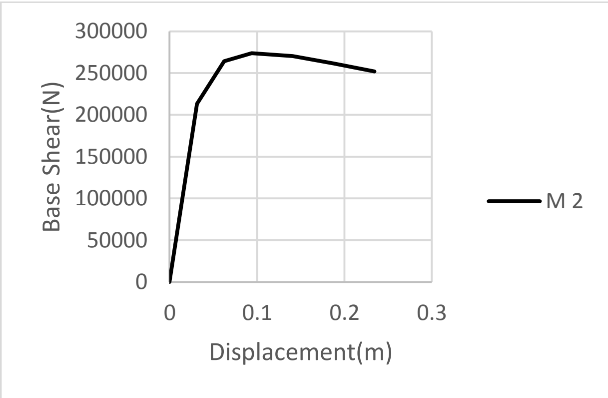

Figure 9. The Load–displacement Curve of the M-2 Model

Table 5. The results of model M-2

Ultimate Strength (kN)	Energy Absorption	Yield Displacement (m)	Ductility	Model Name
274	58.22	0.03	8.36	M-2

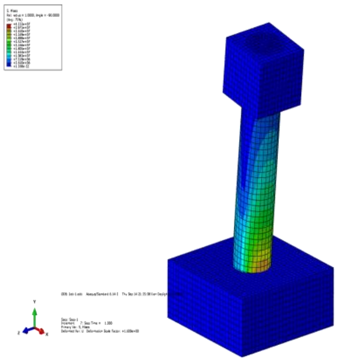

Figure 10. The Onset Yield of the M-2 Model

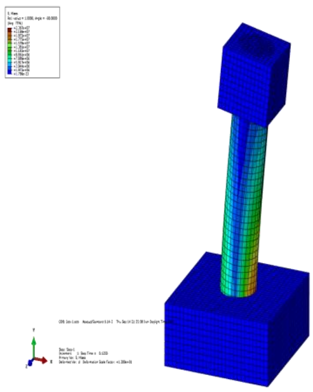

Figure 11. The Sequence Yield of the M-2 Model

Table 6. The Tension in M-2 Members During Failure

Maximum Tension in Concrete	Model Name
41 MPa	M-2

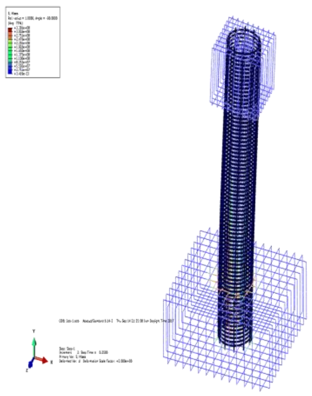

Figure 12. Created Tension in the Longitudinal and Transverse Bars in the M-2 Model

Results of the M-3 model. In this step, the calculation of existing tension in the structure members was performed according to the software results in Table 7. The concrete tension was greater than the cracking module obtained from the $0.6\sqrt{f'_c}$ of value 3.52 MPa. Therefore, cracking in critical points of the column base of the bridge pier was observed. However, the amount of existing tension in the concrete in this model decreased 15% because of steel jacket application, which was attributed to the overall pressure on the concrete. The load–displacement curve for the M-3 model is presented in Figure 14, and the onset yield is shown in Figure 15. Figure 16 presents the sequence yield of the M-3 model and the amount of tension in the members of the M-2 model is presented in Table 8.

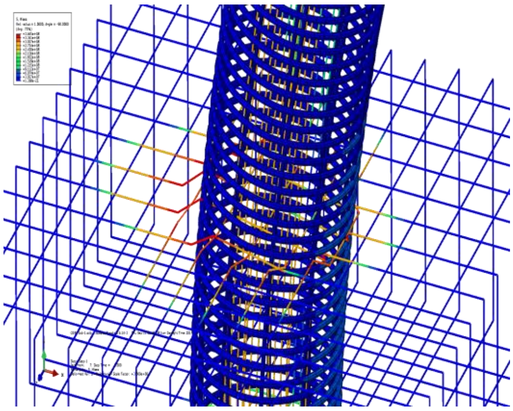

Figure 13. Created Tension in the Longitudinal and Transverse Bars of Foundation in the M-2 Model

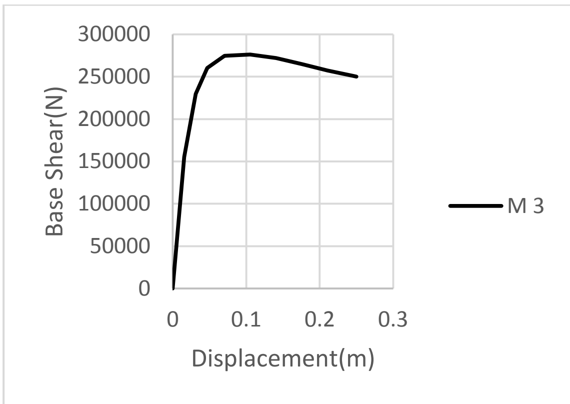

Figure 14. The Load–displacement Curve of the M-3 Model

Table 7. The results of the M-3 model

Ultimate Strength (kN)	Energy Absorption	Yield Displacement (m)	Ductility	Model Name
276	60.1	0.022	11.21	M-3

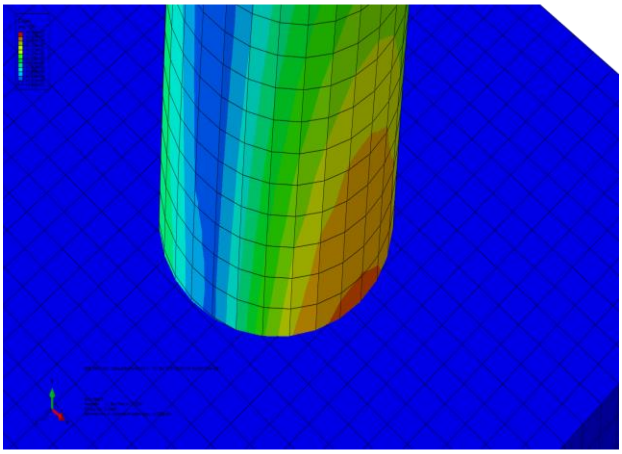

Figure 15. Onset Yield of the M-3 Model

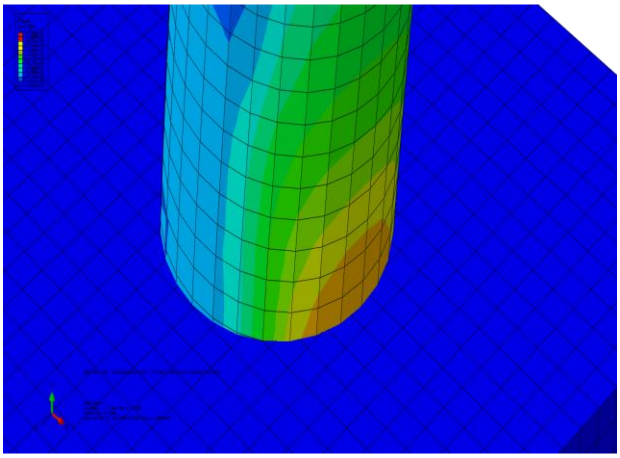

Figure 16. The Sequence Yield of the M-3 Model

Table 8. The Magnitude of Tension in the M-3 Model Members During Failure

Maximum Tension in Concrete	Model Name
39 MPa	M-2

3. The Comparison of Considered Models

A comparison between the shear force–displacement curve is presented in Figure 17; a bar chart of energy absorption is shown in Figure 18; and a bar graph of ultimate strength is presented in Figures 19 and 20 that illustrates a bar chart of ductility for three models in this research.

According to the results in Figures 17 and 18, the steel jacket leads to an increase of 9.5% in energy absorption, and a concrete jacket box with a dimension of 3.5 × 3.5 m causes a 13% increase in energy absorption. Therefore, the concrete jacket application increases the energy absorption in the concrete column of the bridge.

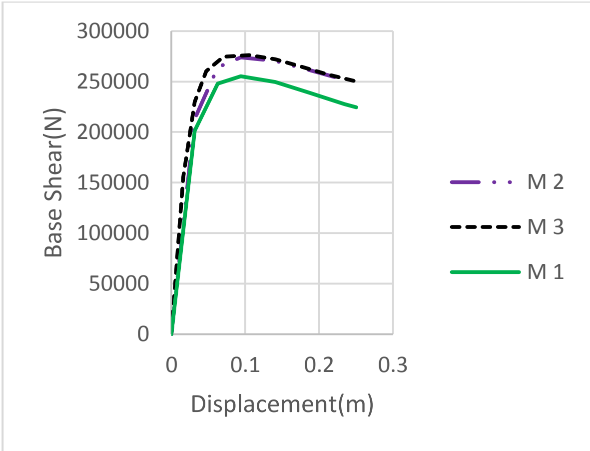

Figure 17. Load–displacement Curves of the Models in this Research

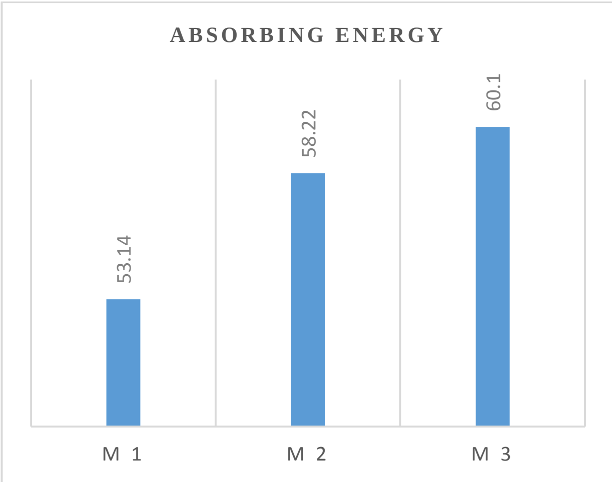

Figure 18. Energy Absorption of the Models in this Research (in kN.m).

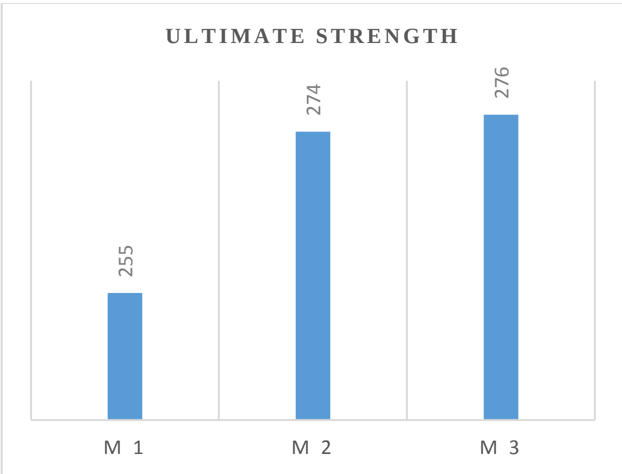

Figure 19. Ultimate strength in the considered models (kN)

According to the results in Figure 19, the steel jacket increased the ultimate strength by 7.5% and the concrete jacket box with a dimension if 3.5 × 3.5 m increased the

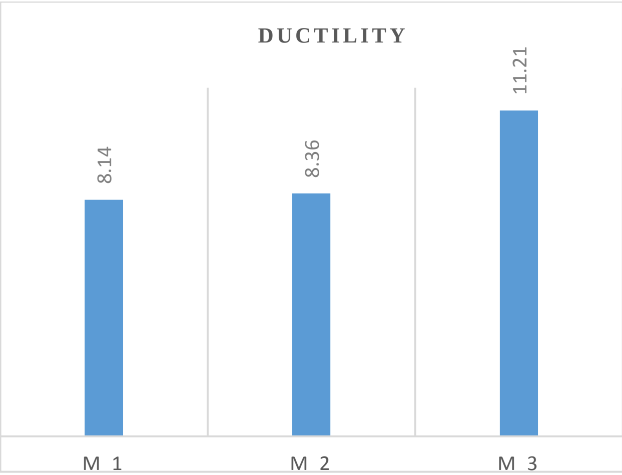

Figure 20. Ductility of the Models in this Research

Figure 21. Pier Bridge Corrosion of the Experimental Model

Figure 22. Pier Bridge Shear Crack of the Experimental Model

Figure 23. Bar Implementation in the Experimental Model of the Pier Bridge

Figure 24. Reinforcement of the Concrete Jacket of the Experimental Model of the Bridge Pier

ultimate strength by 34%. Therefore, the steel and concrete jackets increased the ultimate strength of the concrete column of the bridge.

4. Experimental Model

The experimental model was a model of a damaged and weakened pier of a bridge with concrete jacket reinforcement. The pier damage includes shear crack and concrete and bar corrosion, which was created by flooding, a rapidly flowing river, errors, and administrative problems. Figures 21 and 22 show pier corrosion and the base shear crack of the experimental model of the pier, respectively.

The dimensions of bridge pier were 1.2 m (diameter) and 10 m (height). The dimension of the concrete jacket was 3.5 × 3.5 m with a height of 6 m. After cleaning the damaged surfaces, bar implantation was performed. The size of the longitudinal and spiral bars were 20 and 12 mm, respectively, implemented in two networks with a distance of 20 cm. The distance of longitudinal and spiral bars are @20 and @10, respectively. Figure 23 shows the implementation of bars in the experimental model.

Then, the bar of the box concrete jacket was implemented by connecting it to the implemented bar. The longitudinal and transverse bars of size 20 and 8 are closed at distances of @20 and @8, respectively. After the molding process, concreting with content 400 was used with a super-plasticizer additive. The reinforcement of the concrete jacket of the experimental model of the bridge pier is shown in Figure 24.

The ductility increases by 3% using steel jacket and that of concrete jacket box of dimension 3.5 × 3.5 m is 38%. Therefore, the ductility of the bridge pier system increases with the jacket.

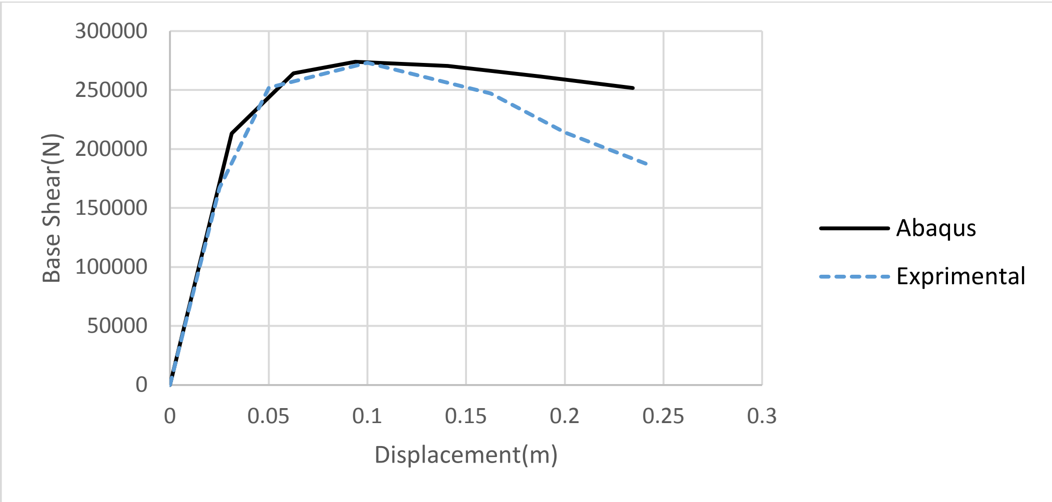

Figure 25. A Comparison of the Experimental Results and Finite Element Analysis

Therefore, based on the software model results, the concrete jacket has the best performance in terms of ductility, ultimate strength, energy coefficient, and load–displacement curve.

5. Conclusions

In this research, the seismic behavior of a steel and concrete jacket-reinforced bridge pier with a dimension of 3.5 × 3.5 m with bar network was considered and compared. Models were analyzed to estimate the seismic parameters as nonlinear geometry and material. It is concluded that: (1) The ductility increases by 3% using a steel jacket and a concrete jacket box with a dimension of 3.5 × 3.5 m, which increases by 38%. Therefore, the ductility of the bridge pier system increases using the steel jacket. (2) According to behavioral models of the reinforcement using steel and concrete box jacket, the concrete jacket has better performance than the steel jacket in terms of energy absorption magnitude, ultimate strength, and ductility. (3) The concrete jacket method was used in experimental modeling, and by comparing the numerical and laboratory results, the accuracy of the type of bridge base pier reinforcement system was determined.

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