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Influence of Conventional Shot Peening Treatment on the Service Life Improvement of Bridge Steel Piles Subjected to Sea Wave Impact

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Abstract: The first goal of the current study is to estimate the fatigue life of the middle steel piles of an integrated bridge installed in water and subject to the impact of sea waves. In the following, the authors have tried to improve the service life of this critical part of the bridge, which is also the main purpose of the study. To this end, conventional shot peening, as one of the most well-known surface treatments, was used. Axial fatigue tests were performed on samples fabricated from IPE-220 steel piles in two states without and with shot peening surface treatment. Next, the modified S-N curve was entered into the finite element software to define the effect of shot peening treatment. Different analysis, including thermal, thermal-structural coupled, and transient dynamic, were performed and various outputs were extracted for the entire structure. In all these analyses, changes in air temperature have been neglected. The most important achievement of this research is the discovery that motionless water cannot cause serious damage to steel piles. Moreover, application of conventional shot peening can increase the fatigue life of steel piles, or in other words the service life of the bridge, subjected to the impact of sea waves by about 22%.

Keywords: bridge; steel piles; sea wave impact; fatigue; shot peening; surface treatment; life improvement

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1. Introduction

One of the most important ways of transporting goods, especially foodstuffs and industrial products, is ground transportation. In addition to being used within cities and countries, this method is recognized as a valuable international communication tool. In this way, many economic exchanges between countries take place through land transportation which, depending on the type of goods, the conditions of the two countries, and other parameters that are beyond the scope of this article, can be done through cargo vehicles, such as trucks and trolleys, or rail trains. In any case, it is necessary to have a ground road (asphalt and dirt, etc.) throughout the route from the origin to the destination. In the meantime, due to various reasons including shortening the length of the road and passing through the heart of the mountain, etc., engineers are forced to use bridges as one of the key components of road construction [1]. In general, these bridges are used to connect two paths separated by different factors such as mountains, valleys, and water, etc. Therefore, it is rare to find a length of land route between two points (e.g., two countries) that is free of any road construction components and has a smooth land road. On the other hand, bridges are classified as large structures consisting of many different components, which are assembled using various techniques such as welding, bolts, and nuts, etc. Many studies have been carried out in the field of estimating and evaluating the strength of bridges, and the most scholars believe that the joints are known as the area prone to failure due to various dynamic loads [2–4]. In fact, fatigue failure is one of the most challenging phenomena in various industries [5–7], especially transportation and construction, and bridges are no exception. In this regard, bridges are subjected to different loads such as additional loads (i.e., different weights of passing vehicles with various vehicle velocities and uneven concentration), natural loads caused by weather conditions (i.e., temperature changes throughout the year that lead to expansion and shrinkage of the bridge deck), or natural loads (e.g., sea wave impact for bridges whose piles are installed in water). Each of these loads alone can cause unique damages to the components which, if sustained, will grow and lead to the final failure of the component. The achievements of researchers in the field of investigating the fatigue behavior of integrated concrete bridges show that fatigue failure occurs in the steel piles located in the middle of the bridge. Hence, the main focus of bridge fatigue studies is on steel piles. Some of these studies are discussed below.

Razmi et al. presented a new guideline to determine deformation type (i.e., elastic, plastic, etc.), deformation value, and fatigue life of piles in integral abutment bridges [8]. To this end, in a case study, they investigated the effect of bridge length as a variable parameter ($122 \leq$ length ≤ 549 m) on the fatigue life of a bridge under daily and seasonal temperature changes, based on a strain-based fatigue damage model. They reported that as bridge length increases, the total strain amplitude rises and then the fatigue life of the bridge decreases exponentially (e.g., the fatigue life obtained for a bridge with lengths of 122 and 549 m is 42 and 9.5 years, respectively). In addition, they stated that the strain amplitude due to seasonal temperature changes is much higher than that due to daily temperature changes. Petursson et al. investigated the fatigue behavior of steel piles under bending caused by temperature variations in two daily and annual modes by performing real-scale tests [9]. They predicted a fatigue life of about 120 years for integral abutment bridges with spans up to 500 m. Recently, Karalar and Dicleli studied the influence of pile orientation on the fatigue behavior of the steel H-shaped piles of a jointless bridge [10]. For this purpose, both finite element simulation and experimental results were used. Moreover, cyclic displacement loading due to temperature changes between summer and winter was considered in bending mode. Finally, they reported that local buckling is more critical than pile orientation for LCF. Furthermore, Razmi et al. used a new continuum damage modeling approach to study fatigue crack initiation and propagation in the piles of integral abutment bridges [11]. In this research, the critical location in the pile was detected based on three-dimensional nonlinear analysis. They reported that a crack can initiate in the pile in less than 6 years but may take about 20 years to reach the web. However, the final failure of the pile may not occur for several decades. Saberi et al. employed operational strain measurements to assess the service life of a bridge under cyclic loading (i.e., fatigue phenomenon) [12]. In this regard, they focused on the bolted connection of a full-scale steel bridge. Wu and Qiu estimated the fatigue life of pile-supported oversea bridges subjected to random ice forces [13]. They stated that ice forces can lead to huge vibrations in marine structures. Moreover, the most common solution to deal with it is to use different cables that hold the structures. Due to the inherent nature of this type of load, which is random, statistical characteristics were used in the analysis [14] so that sea ice properties such as ice speed, ice thickness, and ice strength were considered. In addition, a spectrum model was used to define loading conditions in the software [15]. Next, fatigue analysis was performed using a rain-flow cycle counting technique and Palmgren-Miner's linear damage accumulation rule. The most important achievement obtained in this research is the insight that the use of conical caps improves the fatigue life of a bridge by 45% compared to the use of vertical caps. Abdollahnia et al. investigated the simultaneous influence of temperature changes and sea wave impact on the fatigue life of steel piles in integrated bridges [16]. They reported that in both loading modes, the critical zone, which is prone to failure, is the intermediate steel piles at approximately 1.5 m height from the floor. According to the above literature review, the main focus of the current study is to improve the fatigue lifetime of this component subjected to sea wave impact. To improve the fatigue life of metallic materials, scientists proved that the two factors of compressive residual stress on the surface and an ultrafine grain in the surface are very effective. This conclusion is due to the fact that the initial damages caused by cyclic loading always appear as surface cracks [17–21]. As a result, fatigue properties can be improved by increasing the surface strength. In this regard, different surface treatments have been presented and developed to create the two factors mentioned above. Among them, shot peening is one of the most well-known surface treatments in different industries due to its availability, simple operating mechanism, and low cost [22–26]. Recent research results have shown that the fatigue strength of some metals can be increased from 50% to seven times by using the cold working processes of conventional shot peening (CSP) and severe shot peening (SSP) [27–29]. However, all of these results were in the laboratory environment and considering standard samples, and it is clear that the results will be different for industrial parts and harsh working conditions. Published documents in this field are less common and manufacturers try to reveal their technologies less, which can be one of the drivers of competitiveness in the market. The world of science and academia is beyond this. Therefore, in this paper, CSP was used for the first time to improve the fatigue properties of steel piles of integral concrete bridges installed on water. In other words, the innovation of the present work is justified by the fact that the SP treatment in previous studies was based on different operating conditions (i.e., different values for the most important parameters of the SP such as Alman intensity and surface coverage) and the evaluation of their effects on the fatigue behavior of metals were based on the experimental results of standard samples. However, the steel pile of an integrated bridge is a large and industrial structure. Moreover, new simulations are presented by the authors, which also include standard samples. In summary, in this paper, for the first time, the effect of SP treatment on a large-size structure including different parts (e.g., steel piles) was numerically investigated.

2. Methodology

As mentioned in the introduction, the main objective of this paper is to improve the service life of bridges installed on water by increasing the fatigue strength of intermediate steel piles via CSP treatment. In this way, standard samples were fabricated from steel piles. Some of them were shot peened and then the fatigue test was performed on all the samples to obtain the fatigue properties in two cases of raw material and shot peened samples. Next, in finite element (FE) simulations, the effects of this surface treatment were applied only as a modified S-N diagram for steel piles. Finally, stress analysis and fatigue life calculation were discussed. Figure 1 displays the working flowchart for implementation of this research.

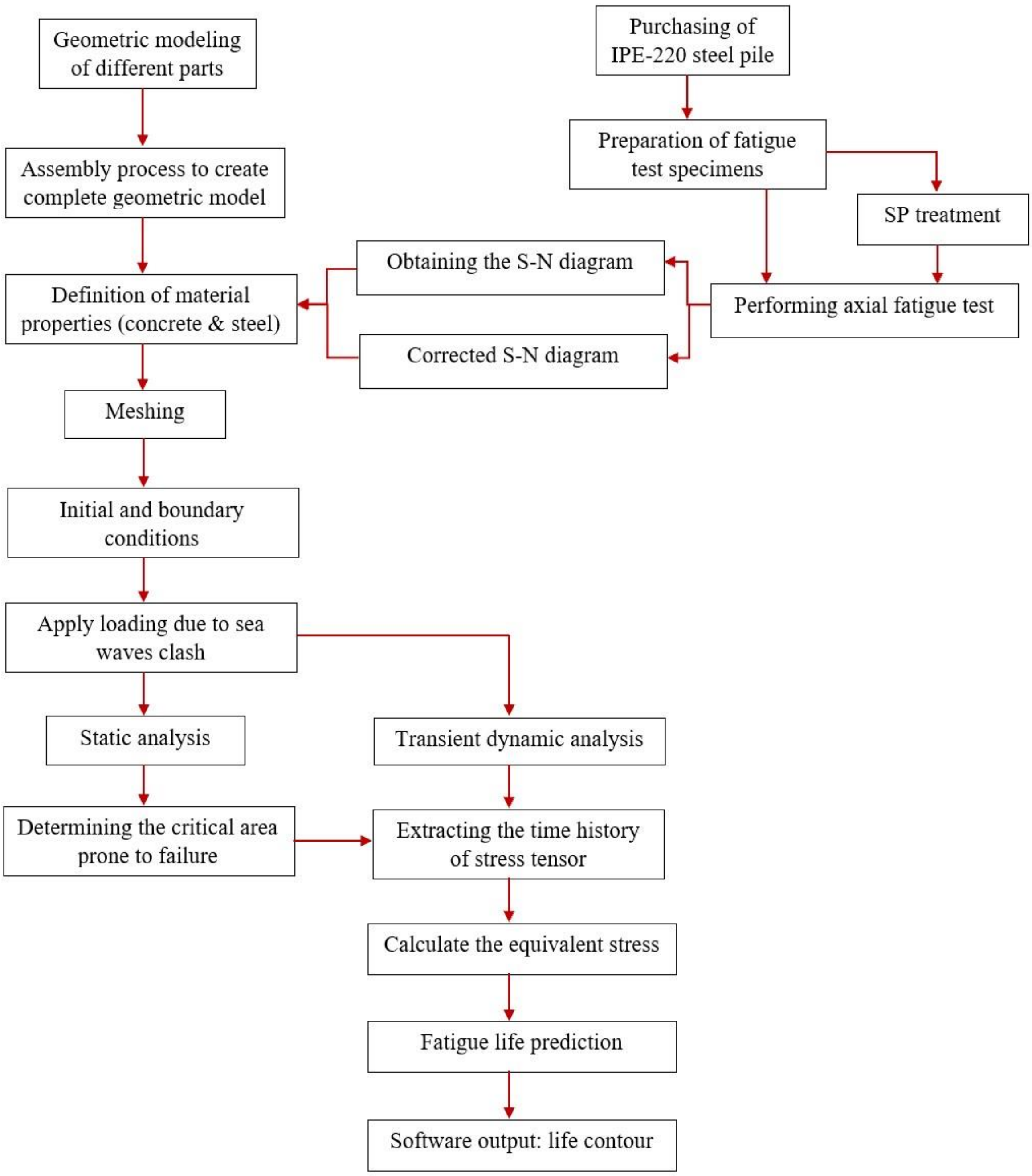


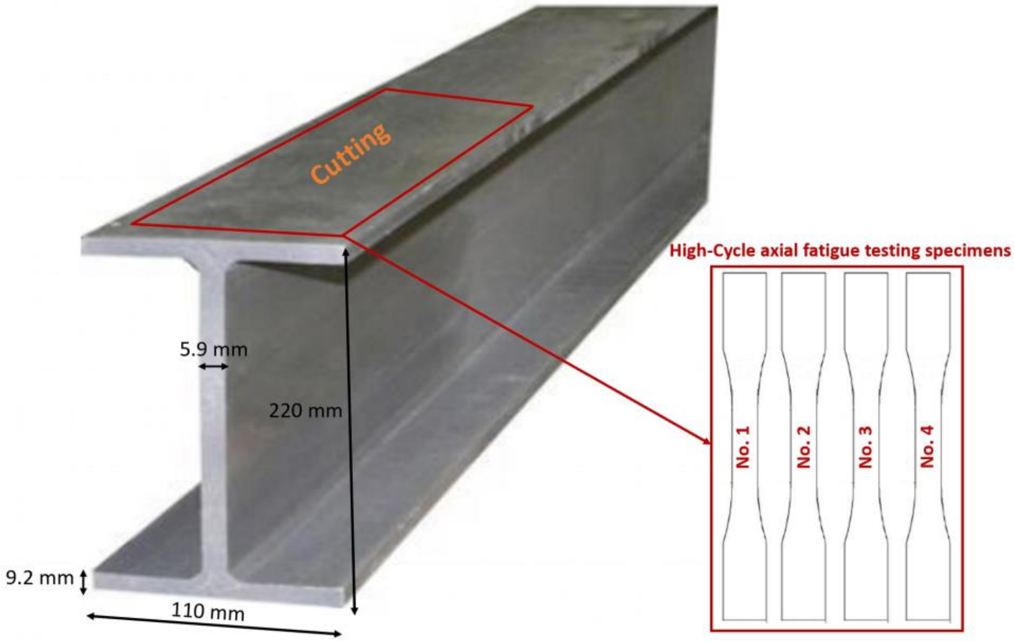
Figure 1. The working flowchart for implementation of this research.

3. Experimental Work

According to the results presented by scholars, and as is clear from the title of the current article, the most critical areas of integrated bridges are the middle steel piles, which are the main focus of this research [1,2,4,16,30]. Therefore, an IPE-220 steel beam was prepared according to the characteristics presented in the previous study [1]. Afterward, axial fatigue test specimens related to the high-cycle regime were fabricated based on the ASTM standard [31]. Figure 2 illustrates the exact place where the specimens were cut from the steel beam as well as the geometry, dimensions, and size of the experiment specimens.

In this way, a CNC wire cutter was used and 48 specimens were prepared. Moreover, the surface roughness of the specimens was checked to be within the acceptable range for the fatigue test. Half of the specimens were considered as raw material and sent for fatigue test without any treatment. Next, SP treatment was performed on the remaining specimens. To this end, steel shots with an average diameter of 0.3 mm and a hardness of about 45 Rockwell C were employed. In addition, a nozzle with compressed air pressure was utilized for performing SP treatment. In addition, the placement angle of the nozzle relative to the target surface was set equal to 90 degrees. Based on the compressed air pressure, the distance between the nozzle and the surface, and other parameters, the speed of the shot hitting the surface was calculated as 50 m/s. Moreover, all SP treatments were performed with Almen intensity of 8 A considering the surface coverage of 100% (i.e., CSP: conventional shot peening). It should be noted that a fatigue specimen has four surfaces. Therefore, SP was done on all four surfaces [32]. In addition, this treatment was not performed on the entire length of the specimen and was only performed on the gauge length. Next, an axial tension-compression dynamic test was performed at room temperature and under controlled environmental conditions according to the requirements of the ISO-17025 standard. All the tests were force controlled and were performed with a force ratio of zero and a frequency of 10 Hz. To extract the high-cycle fatigue (HCF) behavior of the St52 and to study the effectiveness of the intended treatment, fatigue tests were performed at six different stress levels. Moreover, in order to increase the accuracy of the response and to check the repeatability, each test was repeated four times and the mean value of the number of cycles to failure was reported as the fatigue life of the specimen at that stress level [33,34]. The comparison of fatigue results for St52 in two cases without surface treatment and with CSP treatment is presented in Figure 3.

(**a**)



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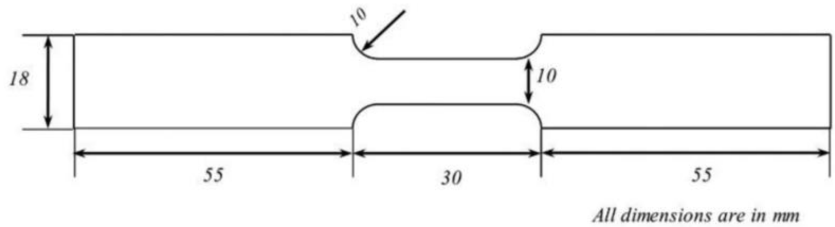


Figure 2. Preparation of experiment specimens: (**a**) exact place where the specimens were cut from the steel beam and (**b**) geometry and dimensions of test specimens according to the ASTM standard for conducting axial HCF test [1].

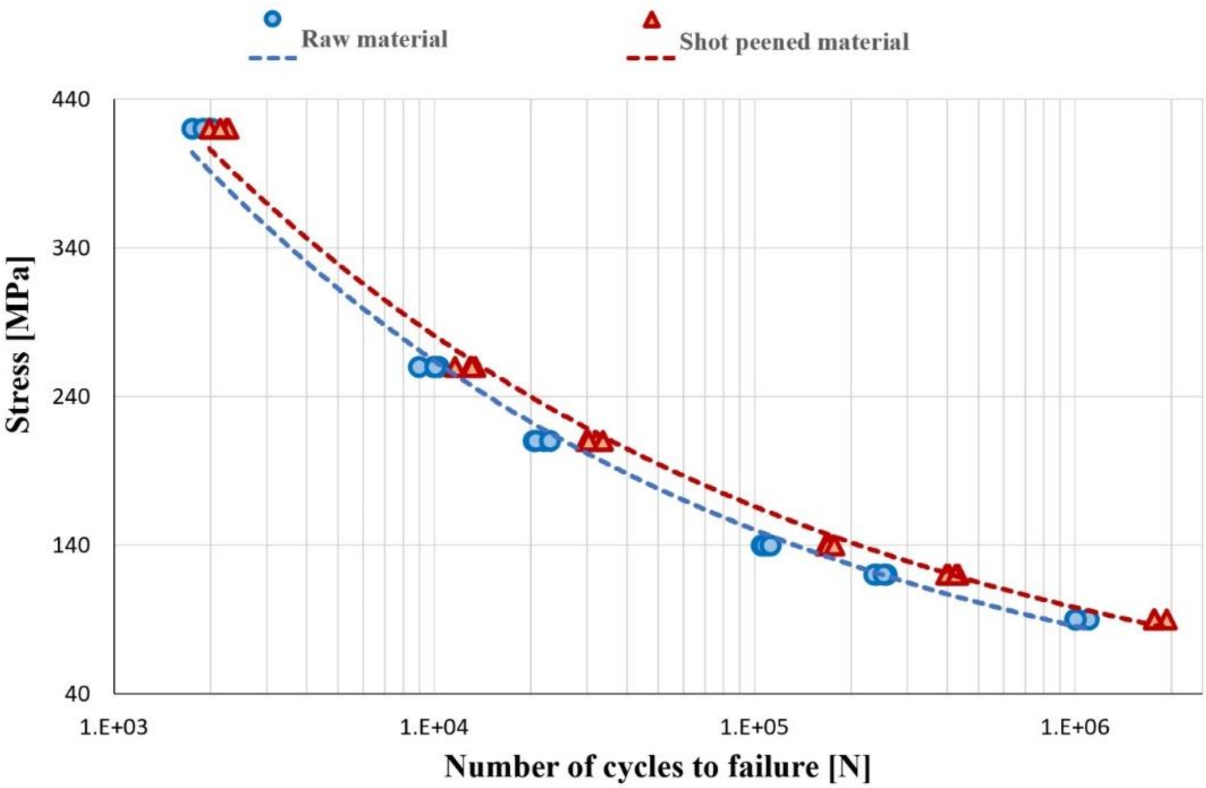


Figure 3. The HCF behavior of shot peened St52 compared to the raw material.

4. Finite Element Analysis

The bridge structure and its concrete (i.e., deck, anchors, and ribs) and steel (i.e., piles) components were modeled in 3D in CATIA V5-6R2021 software, and then the assembly operation was performed. Next, the geometric model was entered into the finite element (FE) software, i.e., ANSYS WORKBENCH 16.0, as an input file. An overview of the three-dimensional modeling and bridge assembly is shown in Figure 4. Moreover, regarding the number of components and their details, see Figure 5. This bridge has four rows of steel piles. Two of them are installed in the middle of the bridge at an equal distance from both sides of the bridge. As shown in Figure 5, there are 12 steel piles in each of the first and last rows of the bridge and 10 steel piles in each of the middle rows. As a result, in general, this structure includes 44 steel piles with IPE-220 specifications. In addition, four cubic concrete beams (the rectangular cross-section with dimensions of 800 × 914 mm and length of 10,856 mm, which is installed in the direction of the deck width) have been used under the deck to connect the steel piles to the deck. Between each of these beams, there are five ribs with IPE-600 specifications. In other words, the total number of ribs in the geometric model is equal to 15. To know the characteristics of IPE-600, refer to [30]. Since the focus of the research series by Professor Reza Kashyzadeh is on steel piles, type IPE-220, and their failure problems under cyclic loading caused by working conditions, the dimensional and appearance characteristics of these piles are given in Table 1. Moreover, it should be noted that in the industry there are two lengths for IPE-220 steel piles, including 3 and 6 m, and in this research, considering the dimensions of the bridge (length and width equal to 104.644 and 11.688 m, respectively), steel piles 6 m long were used.

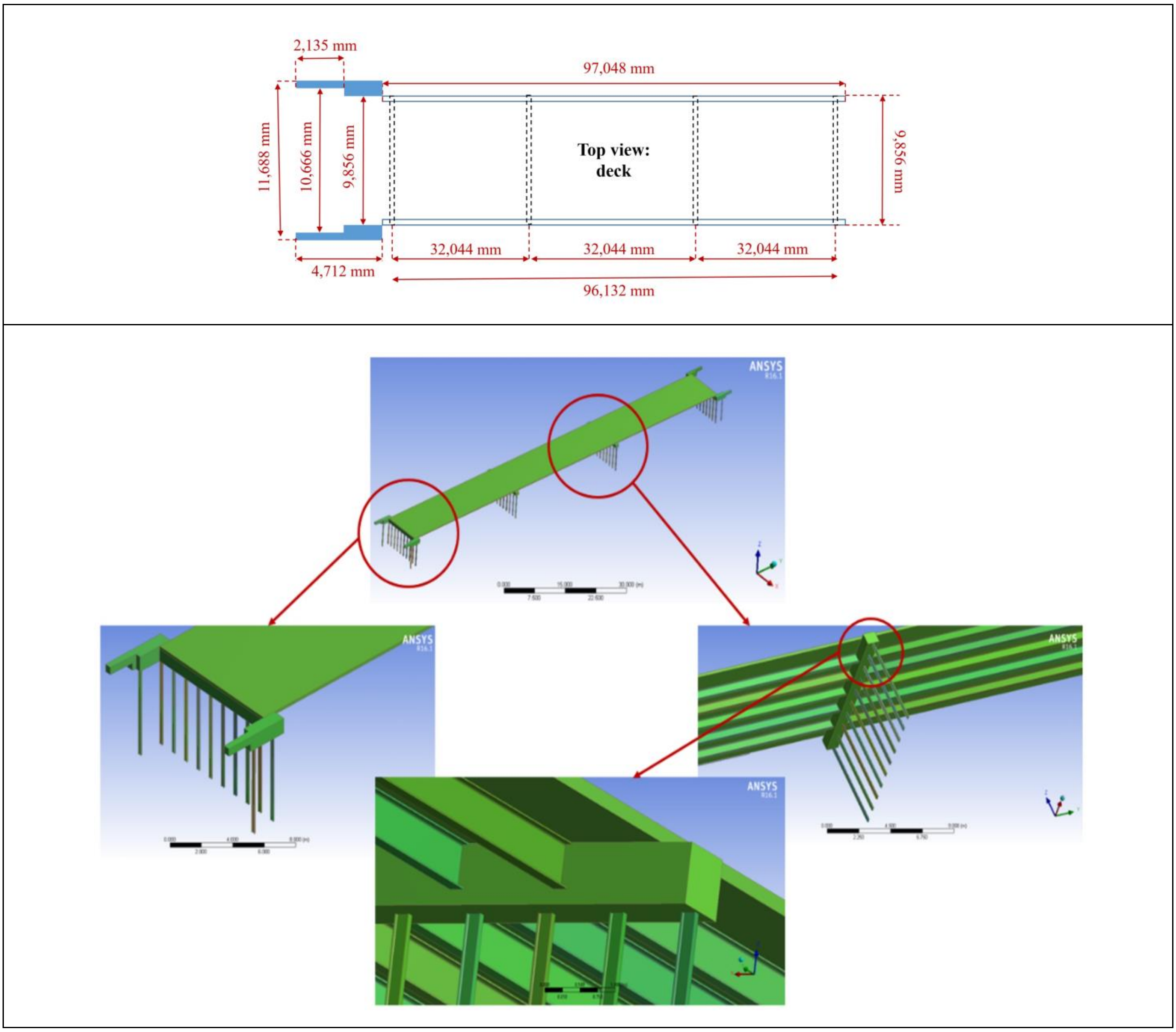


Figure 4. Details of the geometric model of the studied bridge in real scale [1].

To provide the concept of integration in the ANSYS WORKBENCH 16.1 software, the features of continuous deformation and non-separation of components were used [30]. However, it is possible to define boundary conditions between different components and apply loads or other constraints.

Based on previous studies [1,16,30], the concrete parts of the bridge are made of ordinary concrete and the metal parts are made of St52 steel. The temperature changes and subsequent expansion and shrinkage of the bridge deck are not considered and the main focus is on the impact of sea waves. Thus, in order to reduce the computational cost and the software solution time, defining the thermal properties and mechanical properties in terms of temperature was ignored for both materials. Table 2 presents the mechanical properties of these two materials [16]. Furthermore, the fatigue properties of concrete were ignored, and the entire focus of the fatigue analysis was on the steel piles [30]. Furthermore, the fatigue properties of St52 steel were entered into the ANSYS WORKBENCH according to the laboratory results obtained in this research (section No. 3), and in order to apply the effect of shot peening treatment, the laboratory fatigue properties were defined as a modified S-N diagram (red data in Figure 3) for the software.

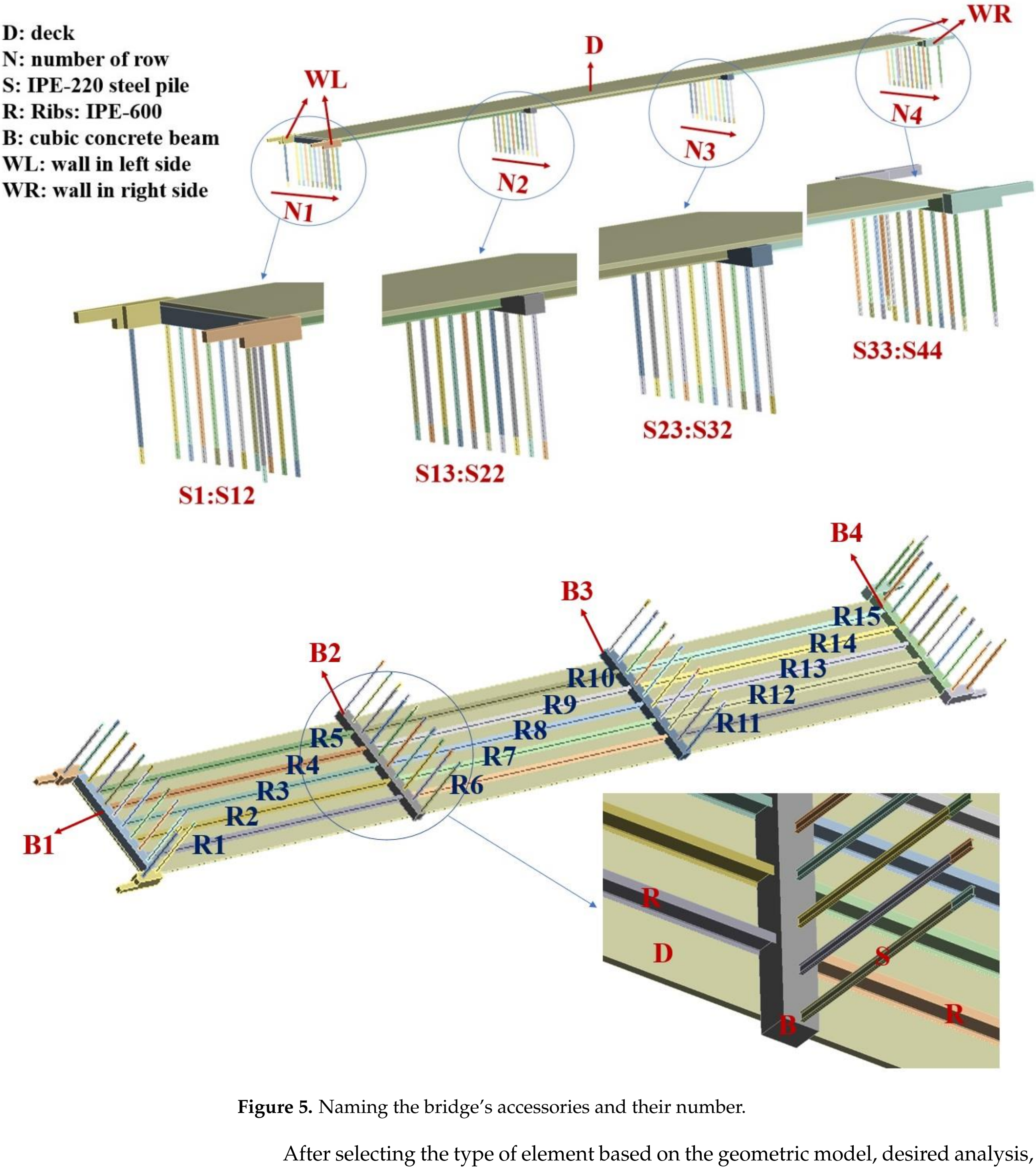
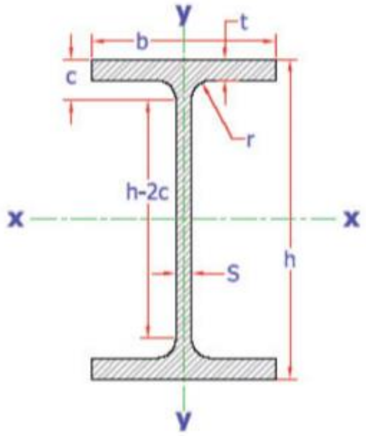


Figure 5. Naming the bridge's accessories and their number.

After selecting the type of element based on the geometric model, desired analysis, and material properties, the meshing process was performed with SOLID185 as a 3D eight-node standard structural solid element. In addition, mesh convergence was studied in order to use the minimum number of elements (reducing the solution time, the need for common desktop computers, etc.) while achieving a reliable answer and acceptable accuracy [35]. For this purpose, the number of divisions of different components, i.e., element size, was considered as input and the maximum deformation in the upper part of the steel piles was considered as output. It is expected that due to the size of the structure, which is very large, changes in the element size of about a few centimeters do not have a significant effect on the results, i.e., deformation value. Therefore, the criterion considered to stop this study was when the difference between the obtained results and the initial state was less than

0.25%. The efforts made at this stage are summarized in Table 3. Finally, the finite element model used in future analyses, containing 121,655 elements (Figure 6).

Table 1. Dimensional and appearance characteristics of IPE-220 steel piles [1].



Symbol	h	B	S	t	r	c	h-2c	A	G	J_x	W_x	I_x	J_y	W_y	I_y
Unit	mm	mm	mm	mm	mm	mm	mm	cm^2	kg/m	cm^4	cm^3	cm	cm^4	cm^3	cm
Value	220	110	5.9	9.2	12	21.2	177	33.4	26.2	2770	252	9.11	205	37.3	2.48

Table 2. Mechanical properties of St52 and ordinary concrete [16].

Parameter	Unit	Value	
		St52	**Ordinary Concrete**
Density	Kg/m^3	7850	2300
Young Modulus	GPa	200	30
Poisson's Ratio	---	0.3	0.18
Bulk Modulus	GPa	166	---
Shear Modulus	GPa	76.92	---
Tensile Yield Stress	MPa	250	---
Compressive Yield Stress	MPa	250	---
Tensile Ultimate Strength	MPa	460	5
Compression Ultimate Strength	MPa	---	41

Table 3. The results of mesh convergence study [16].

Analysis No.	Element Size (m)					Number of Elements	Maximum Deformation (mm)	Difference Compared to the First State
	Deck	**Wall**	**Rib**	**IPE-600**	**IPE-220**			
1	0.5	0.1	0.1	0.1	0.1	327,612	0.0016380	---------
2	0.5	0.2	0.2	0.2	0.2	207,104	0.0016456	0.46
3	1	0.5	0.2	0.2	0.2	121,655	0.0016348	0.19
4	1	0.5	0.5	0.5	0.5	18,643	0.0016262	0.72
5	2	0.5	0.5	0.5	0.5	17,873	0.0016566	1.13
6	2	0.5	0.5	0.8	0.8	10,623	0.0016573	1.18
7	2	0.5	0.5	1	1	8868	0.0016515	0.82

The simulation described here has been validated in a previous study by the corresponding author [4]. Thus, the low-cycle fatigue behavior of a steel pile due to annual temperature variations has been numerically investigated and the results obtained have been compared with the experimental results published by other researchers and the finite element responses of other models. It has been shown that the current model is able to accurately detect the location of the crack initiation. In addition, it predicts fatigue life with a 6.5% difference when compared to reality. This error is quite reasonable and acceptable for simulating such a complex phenomenon due to the simplifications and assumptions considered in the software. Therefore, in order to avoid repetition of the previous content, lengthening the article, and being boring, we instead encourage the reader to follow the validation method and its steps in reference No. 4.

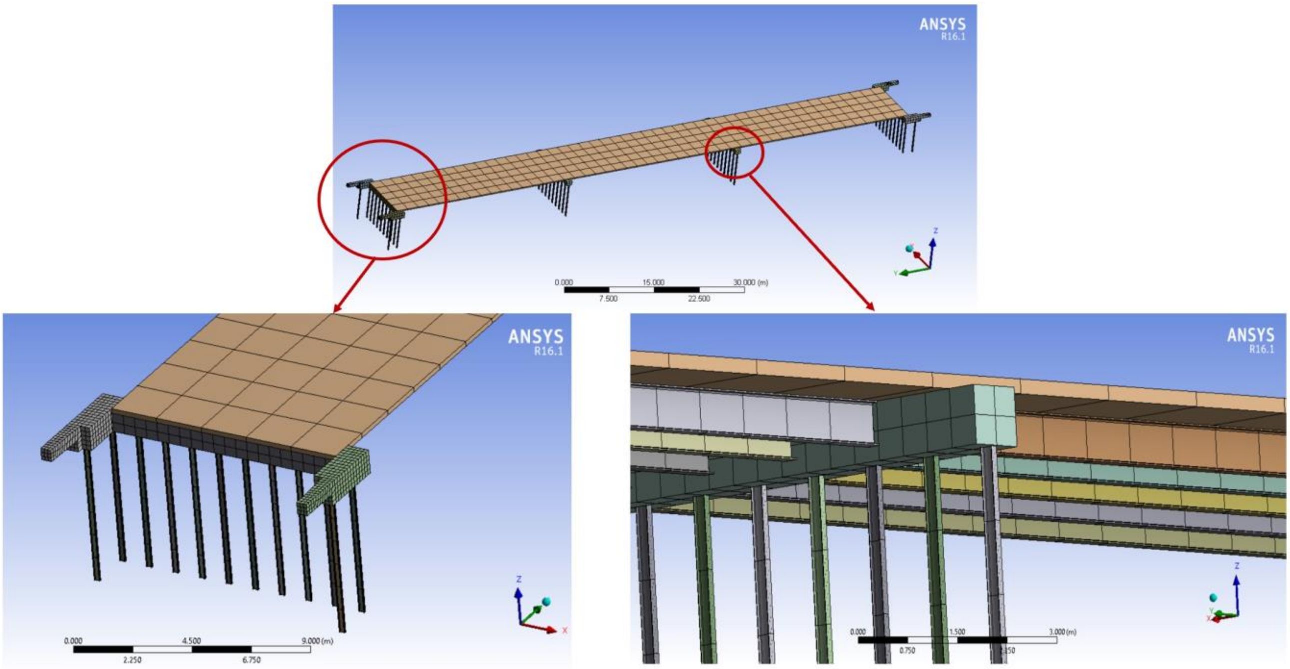


Figure 6. Finite element model of the bridge after mesh convergence study [16].

In this study, it was assumed that the temperature of all of the components of the bridge, especially the steel piles, was equal to 22 °C. Moreover, the water temperature was considered to be 7 °C. Therefore, the sections of the steel piles that are in motionless water, i.e., up to a height of 75 cm from the bottom of the piles, had a temperature of 7 °C. However, it was assumed that these temperatures are constant throughout the year and no temperature gradient occurs in the structure. Moreover, it was assumed for movement restrictions that the bottom surfaces of the middle steel piles are restricted in all degrees of freedom and have no movement. Then, steady-state thermal analysis was performed to extract the temperature distribution in the structure. Next, these data were introduced as input data to the structural analysis. Application of motionless water pressure to the sections of the steel piles that were installed in the water, was done as follows [30]:

$$P = 51.2 \times K \times V^2 \quad (1)$$

in which P represents the pressure of water flow, K is the coefficient that was assumed to be 0.78, based on the geometric shape of the pile cross-section, and V is the speed of the water flow (V = 0.3 m/s). In short, this pressure distribution has a triangle shape with a height of 75 cm, and its base, which has the highest pressure, corresponds to the end of the steel pile. Thermal-structural coupled analysis was performed to identify the area prone to failure, and the future analysis focused only on that area. Then, all outputs were entered into a new structural analysis with the aim of analyzing the impact of sea waves. For this purpose, it was assumed that the direction of waves was constant and in the X direction. Moreover, the waveform with a maximum height of 25 cm was unchanged. Figure 7 shows the history of force applied to steel piles due to waves.

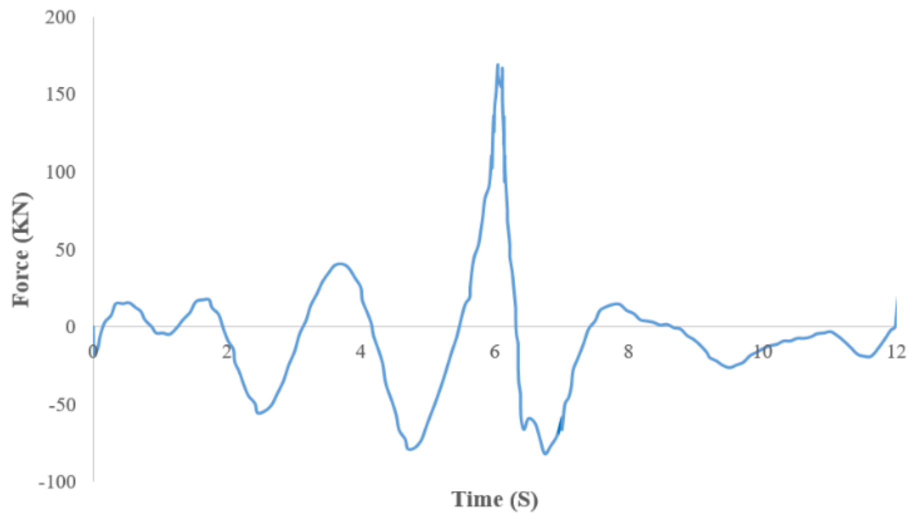


Figure 7. Loading history considered for the impact of sea waves with a height of 25 cm [16].

Transient structural dynamic analysis was performed with software settings comprising 12 steps (period time of one second for each step and a time interval of 0.1 s). In addition, the calculation module based on the large deflection was turned off, and weak springs were automatically controlled by the software. Moreover, displacement convergence was used for response convergence and nonlinear control. The time history of stress tensor components, including all normal and shear stresses, in the critical region (desired node and element) were extracted. Afterward, von Mises equivalent stress was calculated in the critical element. Next, it was used to calculate the fatigue life based on the stress-life criterion. The fatigue life of IPE-220 steel piles was predicted by using nCode DesignLife 16.1 software to count the cycles based on the rain-flow algorithm and employing Palmgren-Miner formulation as the well-known linear damage accumulation rule (LDAR).

5. Results and Discussion

From Figure 3, it is clearly evident that the surface treatment of shot peening leads to the improvement of the fatigue behavior of St52 in the high-cycle regime. In addition, by increasing the number of cycles to failure, the effectiveness of this treatment increases. The reason that shot peening treatment is not very useful in the low-cycle fatigue area can be attributed to the creation of surface roughness in the sample and in the LCF test. This roughness acts as the stress concentration and local plastic deformation occurs. This shows that the effect of surface roughness dominates the influence of compressive residual stress in the LCF test. For example, CSP leads to improved fatigue properties of about 13% and 76% corresponding to loading stresses of 420 and 90 MPa, respectively. Since the fatigue life of large structures such as bridges is in the high-cycle or very high-cycle regions, this surface treatment is expected to affect more than the previously mentioned values. The data reported in Figure 3 are related to the laboratory results on standard specimens, and thus the actual conditions in terms of loading, geometry, and size of the structure should be considered and then commented. The characteristics of the temperature distribution obtained from the steady-state thermal analysis are shown in Figure 8.

In Figure 8, the temperature profile does not show any strong temperature gradient. Therefore, this temperature range does not create any stress that leads to failure or damage to the structure. Next, the von Mises equivalent stress distribution due to the pressure of motionless water on the bridge steel piles is shown in Figure 9. The results of thermal-structural coupled analysis indicate that the maximum stress created in steel piles is around 10 MPa. Firstly, this amount is very small and insignificant compared to a large structure like a bridge. Secondly, this stress on the steel piles is constant and therefore not considered as a cyclic load. Finally, it can be concluded that the pressure of motionless water has no effect on the fatigue life of the structure or is negligible and can be ignored [30].

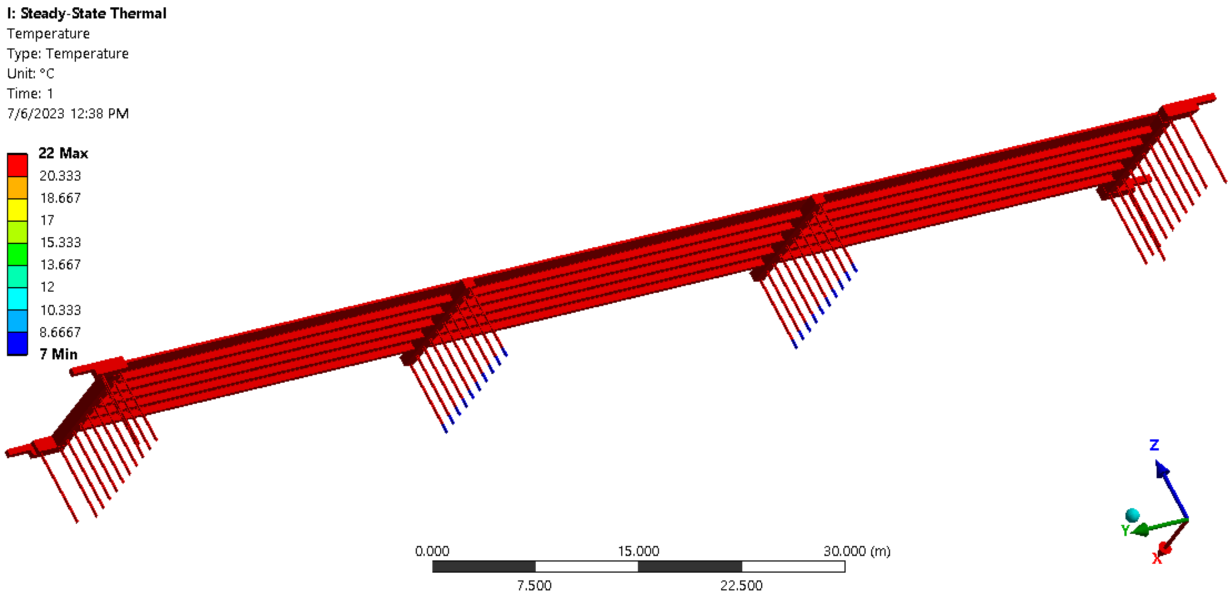


Figure 8. Temperature distribution in the bridge as a result of steady-state thermal analysis.

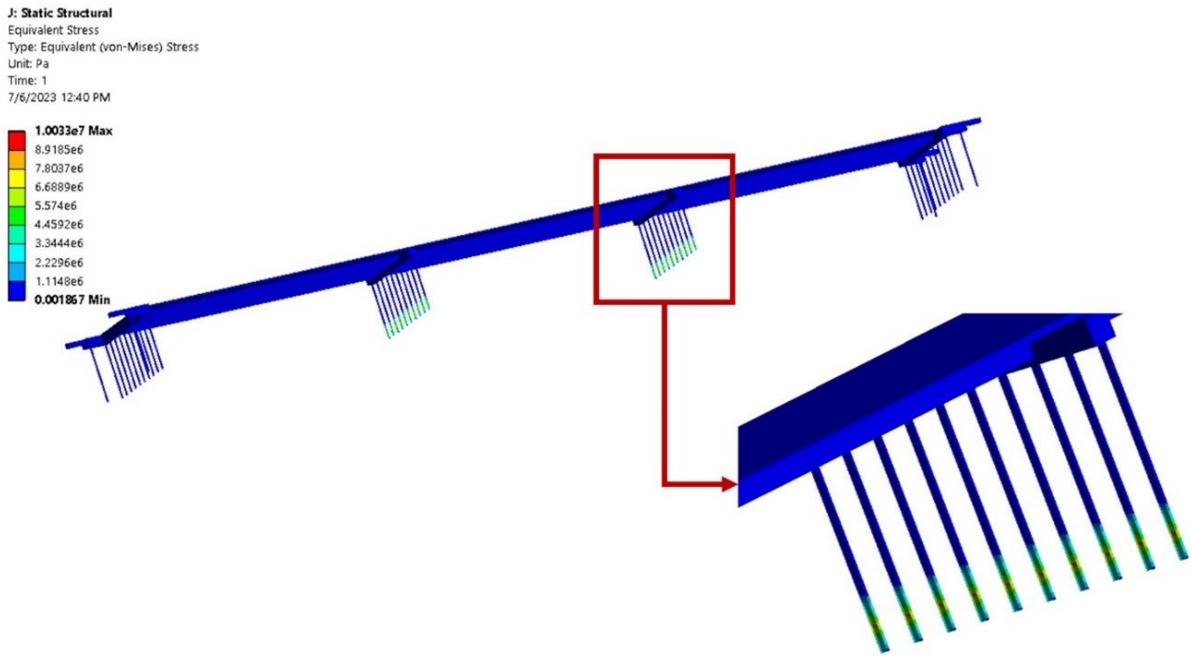


Figure 9. Von Mises equivalent stress contour in the bridge steel piles due to the pressure of motionless water and temperature difference of air (22 °C) and water (7 °C).

As is clear from the results of thermal-structural coupled analysis, the steel piles in the middle of the bridge are known as the critical area (i.e., N2 and N3 in Figure 5). To identify the critical zone more accurately, in Figure 10 the stress concentration is the highest in the steel pile with the location S28 in row N3. In addition, the maximum stress occurs in the bridge foundation up to a certain height, which is consistent with the achievements of other studies that state that the damage occurs in the lower third of the steel pile [2,4,16]. In this case study, the damage occurs at a height of 150 cm from the bottom of the steel pile. Hence, element No. 56,042 was considered as the most critical area and future calculations are focused on this area [16].

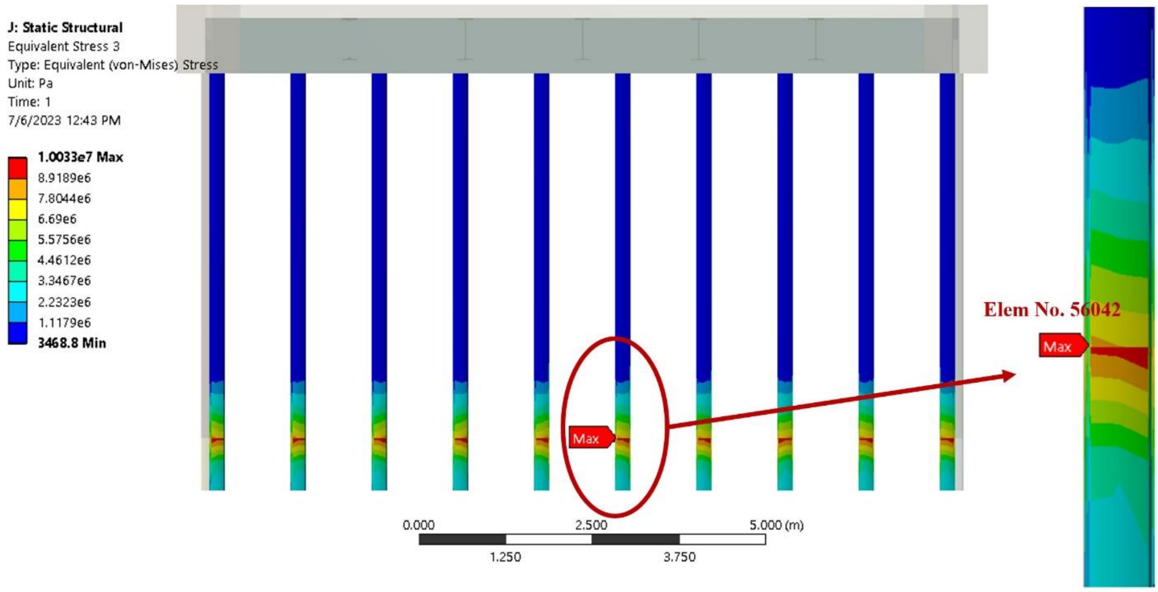


Figure 10. The exact location of the critical element prone to failure: element No. 56,042 at location of S28 in row N3.

Deformation of the N3 row steel piles in different directions as the result of the second thermal-structural coupled analysis in the critical zone of the bridge is given in Figure 11.

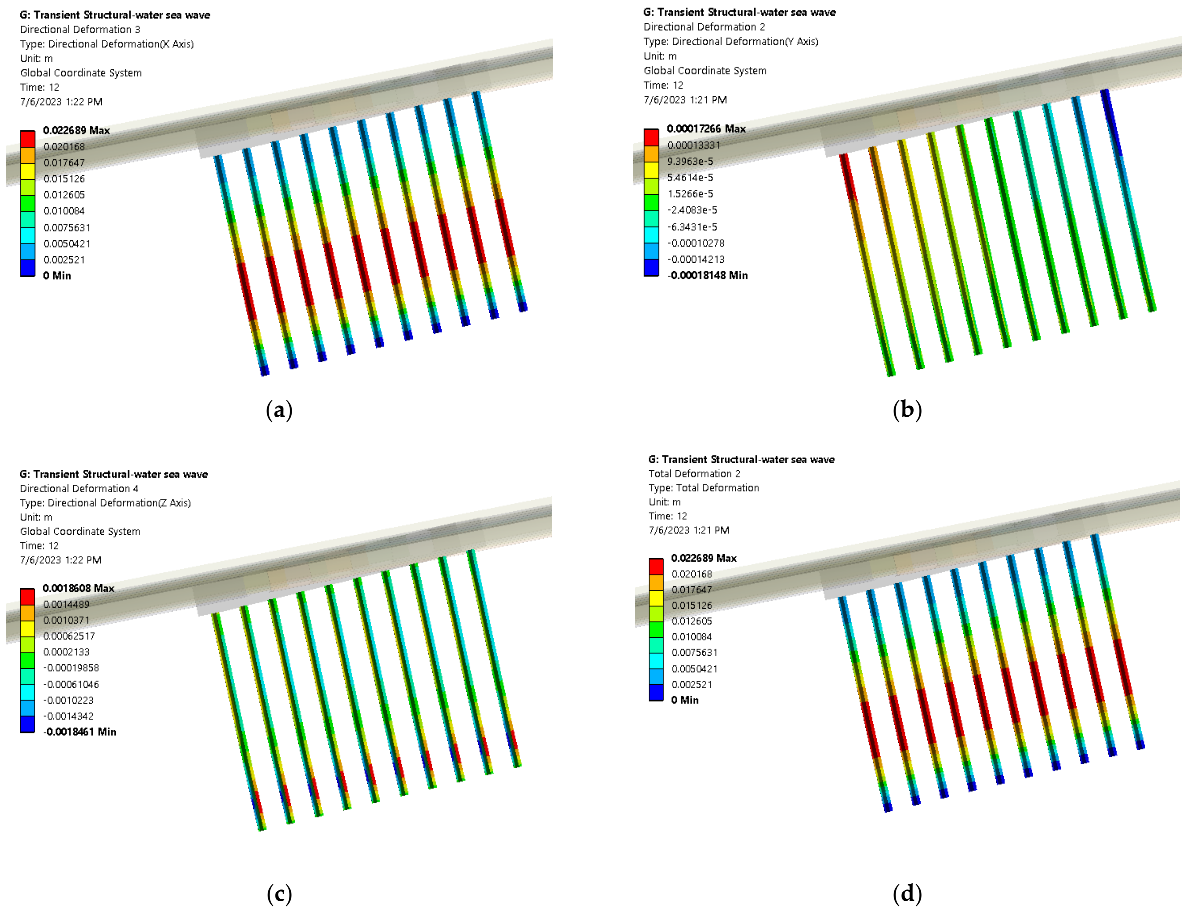


Figure 11. Deformation contours in N3 row steel piles of the bridge due to the impact of waves: (**a**) deformation in X direction, (**b**) deformation in Y direction, (**c**) deformation in Z direction, and (**d**) total deformation.

From Figure 11d, the largest deformation occurred in the steel piles at the height detected in the previous step, i.e., in the height range of 50 to 150 cm from the bottom. In addition, this deformation is mostly affected by the deformation in the X direction, which is the direction of the sea waves. Next, the life contours of S28 steel pile as a result of fatigue analysis for both modes of using St52 without surface treatment and shot peened St52 are demonstrated in Figure 12. Cycle count by rain-flow method for von Mises equivalent stress corresponding to one loading block was equal to 48 cycles. This value is consistent with the ranges defined in previous studies based on a variety of equivalent stress criteria for variable amplitude multiaxial loadings [16].

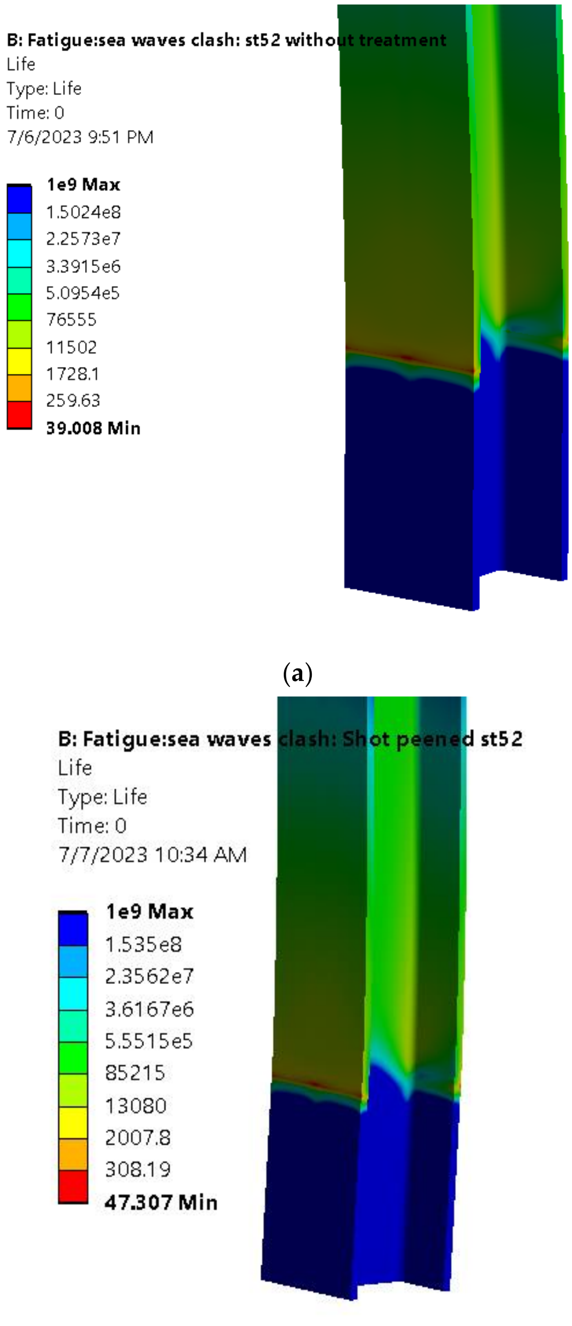


Figure 12. Fatigue life contour of IPE-220 steel pile subjected to sea wave impact considering different conditions for its material, including (**a**) St52 without surface treatment [30] and (**b**) shot peened St52.

As shown in Figure 12, the fatigue life of an S28 steel pile in the initial state (i.e., use of St52 without surface treatment for the material) is equal to 39 years, which is consistent with previous achievements [30]. Meanwhile, the conventional shot peening treatment detailed in this case study extends the fatigue life of the S28 steel pile by more than 47 years.

6. Conclusions

This research is part of a series of previous studies with the aim of developing science and technology in large structures such as bridges. The first step was to predict the fatigue life of steel piles of a real-scale bridge installed in motionless water. After that, the prediction of the fatigue life caused by the impact of sea waves was discussed, and then an attempt was made to improve the life of the bridge by using one of the most famous methods of surface treatment methods, i.e., conventional shot peening. In other words, the main goal of this research was to improve the service life of the bridge by applying surface treatment. The most important results obtained in this case study are as follows:

1. Ignoring temperature variations throughout the year, the temperature difference between water and air is not large enough to cause severe temperature gradients in the system. Therefore, it does not cause any damage to the structure.
2. The maximum stress applied to the steel piles of the bridge due to the pressure of motionless water is about 10 MPa, and this value is much less than can damage the bridge. This load is constant and does not affect the fatigue phenomenon on its own.
3. The area prone to failure in the bridge is the steel piles installed in the water, in other words, the middle piles. In this case study, it was shown that row N3 is the most critical part. Within this, S28 steel pile gets the most damage. Moreover, this damage occurs in the height range between the floor and 150 cm.
4. Fatigue analysis results show that the life of the S28 steel pile due to impact of sea waves is about 39 years, and this value reaches 47 years when using surface shot peening treatment.
5. In the finite element simulation, the modified S-N curve obtained from the experimental tests was used as the definition of the shot peening effect. Finally, the FE results reveal that this treatment could increase the fatigue life of steel piles subjected to sea wave impact by 22%.

It should be noted that, in this case study, it was assumed that the entire length of the steel piles (i.e., 6 m) and all of the surfaces and edges were shot peened. Now, in order to reduce the execution time and save money, only the critical area can be shot peened. Therefore, in future research, the authors will deal with the process of local shot peening in industrial parts. In addition, they will try to investigate the effect of different types of shot peening treatment, such as severe shot peening (i.e., shot peening with different intensities, etc.) on the fatigue life of steel piles. Moreover, the authors are looking for a parametric analysis to optimize the parameters of this surface treatment with the aim of maximizing the service life of steel piles installed in water.

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References

1. Abdollahnia, H.; Alizadeh Elizei, M.H.; Reza Kashyzadeh, K. Application of Probabilistic Approach to Investigate Influence of Details in Time History of Temperature Changes on the HCF Life of Integrated Bridge Steel Piles Installed on Water. *J. Mar. Sci. Eng.* **2022**, *10*, 1802. [CrossRef]
2. Karalar, M.; Dicleli, M. Effect of thermal induced flexural strain cycles on the low cycle fatigue performance of integral bridge steel H-piles. *Eng. Struct.* **2016**, *124*, 388–404. [CrossRef]
3. Ng, K.W.; Garder, J.; Sritharan, S. Investigation of ultra high performance concrete piles for integral abutment bridges. *Eng. Struct.* **2015**, *105*, 220–230. [CrossRef]
4. Abdollahnia, H.; Elizei, M.H.A.; Kashyzadeh, K.R. Low-cycle fatigue behavior of H-shaped steel piles of an integral concrete bridge subjected to temperature variations. *Mater. Today Proc.* **2021**, *46*, 1657–1662. [CrossRef]
5. Amiri, N.; Shaterabadi, M.; Reza Kashyzadeh, K.; Chizari, M. A comprehensive review on design, monitoring, and failure in fixed offshore platforms. *J. Mar. Sci. Eng.* **2021**, *9*, 1349. [CrossRef]
6. Fahmi, A.T.W.K.; Kashyzadeh, K.R.; Ghorbani, S. A comprehensive review on mechanical failures cause vibration in the gas turbine of combined cycle power plants. *Eng. Fail. Anal.* **2022**, *134*, 106094. [CrossRef]
7. Reza Kashyzadeh, K.; Amiri, N.; Maleki, E.; Unal, O. A Critical Review on Improving the Fatigue Life and Corrosion Properties of Magnesium Alloys via the Technique of Adding Different Elements. *J. Mar. Sci. Eng.* **2023**, *11*, 527. [CrossRef]
8. Razmi, J.; Ladani, L.; Aggour, M.S. Fatigue life of piles in integral-abutment bridges: Case study. *J. Bridge Eng.* **2013**, *18*, 1105–1117. [CrossRef]
9. Petursson, H.; Möller, M.; Collin, P. Low-cycle fatigue strength of steel piles under bending. *Struct. Eng. Int.* **2013**, *23*, 278–284. [CrossRef]
10. Karalar, M.; Dicleli, M. Effect of pile orientation on the fatigue performance of jointless bridge H-piles subjected to cyclic flexural strains. *Eng. Struct.* **2023**, *276*, 115385. [CrossRef]
11. Razmi, J.; Ladani, L.; Aggour, M.S. Fatigue crack initiation and propagation in piles of integral abutment bridges. *Comput.-Aided Civ. Infrastruct. Eng.* **2013**, *28*, 389–402. [CrossRef]
12. Saberi, M.R.; Rahai, A.R.; Sanayei, M.; Vogel, R.M. Bridge fatigue service-life estimation using operational strain measurements. *J. Bridge Eng.* **2016**, *21*, 04016005. [CrossRef]
13. Wu, T.; Qiu, W. Fatigue life prediction of pile-supported sea-crossing bridges subject to random ice forces. *J. Constr. Steel Res.* **2022**, *190*, 107156. [CrossRef]
14. Kashyzadeh, K.R. A new algorithm for fatigue life assessment of automotive safety components based on the probabilistic approach: The case of the steering knuckle. *Eng. Sci. Technol. Int. J.* **2020**, *23*, 392–404. [CrossRef]
15. Reza Kashyzadeh, K.; Ostad-Ahmad Ghorabi, M.J.; Arghavan, A. Fatigue life prediction of package of suspension automotive under random vibration based on road roughness. *Med. J. Model. Simul.* **2015**, *4*, 050.
16. Abdollahnia, H.; Alizadeh Elizei, M.H.; Reza Kashyzadeh, K. Multiaxial fatigue life assessment of integral concrete bridge with a real-scale and complicated geometry due to the simultaneous effects of temperature variations and sea waves clash. *J. Mar. Sci. Eng.* **2021**, *9*, 1433. [CrossRef]
17. Maleki, E.; Unal, O.; Seyedi Sahebari, S.M.; Reza Kashyzadeh, K. A Novel Approach for Analyzing the Effects of Almen Intensity on the Residual Stress and Hardness of Shot-Peened (TiB + TiC)/Ti–6Al–4V Composite: Deep Learning. *Materials* **2023**, *16*, 4693. [CrossRef]
18. Songsong, S.; Xiaolin, G. The HCF property research of quenched crankshaft based on the stress field intensity method and the multi-physic field Coupling Numerical simulation approach. *Int. J. Fract.* **2023**. [CrossRef]
19. Schubnell, J.; Carl, E.; Widerspan, V.; Collmann, M. Determination of Loading and Residual Stresses on Offshore Jacket Structures by X-ray Diffraction. *J. Mar. Sci. Eng.* **2023**, *11*, 1304. [CrossRef]
20. Reza Kashyzadeh, K.; Farrahi, G.H.; Ahmadi, A.; Minaei, M.; Ostad Rahimi, M.; Barforoushan, S. Fatigue life analysis in the residual stress field due to resistance spot welding process considering different sheet thicknesses and dissimilar electrode geometries. *Proc. Inst. Mech. Eng. Part L J. Mater. Des. Appl.* **2023**, *237*, 33–51. [CrossRef]
21. Mahmoudi, A.H.; Ghasemi, A.; Farrahi, G.H.; Sherafatnia, K. A comprehensive experimental and numerical study on redistribution of residual stresses by shot peening. *Mater. Des.* **2016**, *90*, 478–487. [CrossRef]
22. Maleki, E.; Unal, O.; Guagliano, M.; Bagherifard, S. The effects of shot peening, laser shock peening and ultrasonic nanocrystal surface modification on the fatigue strength of Inconel 718. *Mater. Sci. Eng. A* **2021**, *810*, 141029. [CrossRef]
23. Amanov, A.; Karimbaev, R.; Maleki, E.; Unal, O.; Pyun, Y.S.; Amanov, T. Effect of combined shot peening and ultrasonic nanocrystal surface modification processes on the fatigue performance of AISI 304. *Surf. Coat. Technol.* **2019**, *358*, 695–705. [CrossRef]
24. Maleki, E.; Unal, O.; Kashyzadeh, K.R. Effects of conventional, severe, over, and re-shot peening processes on the fatigue behavior of mild carbon steel. *Surf. Coat. Technol.* **2018**, *344*, 62–74. [CrossRef]

25. Qin, Z.; Li, B.; Chen, T.; Chen, C.; Chen, R.; Ma, H.; Xue, H. Comparative study of the effects of conventional shot peening and ultrasonic shot peening on very high cycle fatigue properties of GH4169 superalloy. *Int. J. Fatigue* **2023**, *175*, 107799. [CrossRef]
26. Maleki, E.; Bagherifard, S.; Unal, O.; Jam, A.; Shao, S.; Guagliano, M.; Shamsaei, N. Superior effects of hybrid laser shock peening and ultrasonic nanocrystalline surface modification on fatigue behavior of additive manufactured AlSi10Mg. *Surf. Coat. Technol.* **2023**, *463*, 129512. [CrossRef]
27. Farrahi, G.H.; Lebrijn, J.L.; Couratin, D. Effect of shot peening on residual stress and fatigue life of a spring steel. *Fatigue Fract. Eng. Mater. Struct.* **1995**, *18*, 211–220. [CrossRef]
28. Bagherifard, S.; Fernandez-Pariente, I.; Ghelichi, R.; Guagliano, M. Effect of severe shot peening on microstructure and fatigue strength of cast iron. *Int. J. Fatigue* **2014**, *65*, 64–70. [CrossRef]
29. Maleki, E.; Unal, O.; Kashyzadeh, K.R. Fatigue behavior prediction and analysis of shot peened mild carbon steels. *Int. J. Fatigue* **2018**, *116*, 48–67. [CrossRef]
30. Abdollahnia, H.; Alizadeh Elizei, M.H.; Reza Kashyzadeh, K. Fatigue life assessment of integral concrete bridges with H cross-section steel piles mounted in water. *J. Fail. Anal. Prev.* **2020**, *20*, 1661–1672. [CrossRef]
31. *ASTM E466-15*; Standard Practice for Conducting Force Controlled Constant Amplitude Axial Fatigue Tests of Metallic Materials. ASTM International: West Conshohocken, PA, USA, 2015.
32. Maleki, E.; Farrahi, G.H.; Reza Kashyzadeh, K.; Unal, O.; Gugaliano, M.; Bagherifard, S. Effects of conventional and severe shot peening on residual stress and fatigue strength of steel AISI 1060 and residual stress relaxation due to fatigue loading: Experimental and numerical simulation. *Met. Mater. Int.* **2021**, *27*, 2575–2591. [CrossRef]
33. Kashyzadeh, K.R.; Arghavan, A. Study of the effect of different industrial coating with microscale thickness on the CK45 steel by experimental and finite element methods. *Strength Mater.* **2013**, *45*, 748–757. [CrossRef]
34. Arghavan, A.; Reza Kashyzadeh, K.; Asfarjani, A.A. Investigating effect of industrial coatings on fatigue damage. *Appl. Mech. Mater.* **2011**, *87*, 230–237. [CrossRef]
35. Farrahi, G.H.; Kashyzadeh, K.R.; Minaei, M.; Sharifpour, A.; Riazi, S. Analysis of resistance spot welding process parameters effect on the weld quality of three-steel sheets used in automotive industry: Experimental and finite element simulation. *Int. J. Eng.* **2020**, *33*, 148–157. [CrossRef]