Stress analysis of a sample marine crane's boom under static loading condition

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Abstract

Marine cranes are important loading/unloading equipment in use at ports for transferring goods to/from marine vessels such as a merchantman. One of the most important design decision criteria for marine cranes is to ensure that the stress magnitudes remain below the maximum allowable stress values on the crane's structural members during their operation. However, a full scale test to investigate such loading during design validation may be a very expensive practice or almost impossible. Therefore, it is considered more practicable to work with scale models to investigate stress distributions and likely deformations physically. This study presents stress analysis for a sample marine crane's boom, which is originally designed with a boom length of 9 m using experimental and numerical methods. To enable the experimental part of the study, a 1:10 scale model of a sample marine crane's boom has been considered. Strain measurement techniques (using strain-gauges) were utilised for the experimental stress measurement of the scale model. Finite Element Method (FEM) as a numerical method was used to map and simulate stress distribution on the scaled boom structure. The results showed that significant information about stress distribution on the crane members could be obtained from FEM simulation. A good correlation between experimental and simulation values of stresses were observed until the boom's plastic deformation failure.

Keywords: Marine Crane Design, Stress Analysis, FEM, CAE

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INTRODUCTION

As a type of industrial crane, marine cranes can be described as the equipment specifically used in ports and on large ships for loading/unloading, moving and transport operations of heavy materials. Their design features vary widely according to their major operational specifications such as: type of motion of the crane structure; weight and type of the load; location of the crane; geometric features; operating regimes; and environmental conditions (Shinde, 2009).

Marine cranes are designed to be operated under various loading type for their static and dynamic loading conditions which may appear during usual and unusual operations in the ports or open sea. Mostly, they work under high level loading conditions, so marine cranes are manufactured as steel constructions. Structural stresses, which may occur because of these high level loading conditions, should be examined / predicted because they have an important role in the design decision or improvement criteria. Therefore, the individual design phenomenon of the structural and functional crane members should be handled as a vital issue.

Marine crane's design, analysis, manufacture, set up and test procedures are specified with international standards/rules according to the purpose of the marine/offshore equipment to be designed (such as DIN EN 13852-1, BS EN 13001-1:2004+A1: 2009 etc.), however, traditionally the analysis of large mechanical appliances such as marine cranes with considerable functional motions can be divided into three categories: structural analysis; mechanism/motion analysis; and hydraulic system analysis (Langen et al., 2011). Within the structural analysis, it considers the calculation of stresses and deformations of members/elements, joints and links, under the assumption that the un-deformed geometry of the structure remains constant during the analysis. At this juncture, it is possible to consider two main types of stress analysis as the criteria to be discussed in the design validation process. The first is conceptual, where the structure does not yet exist and the analyst is given reasonable leeway to define geometry, material, loads, and so on. The pre-eminent way of doing this nowadays is with the finite element method (FEM). The second analysis is where the structure (or a prototype) exists, and it is this particular existing structure that must be analysed (Doyl, 2004). At this point, it is possible to use both methodologies as a focus by comparing them which may be very useful and more reliable within new design, design development decisions or design validation processes for marine cranes.

Although full size design issues for marine cranes is a long and detailed process, as a part of design decision criteria, this study focuses on the stress analysis using both experimental and

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FEM based simulation methods for design validation/test of a sample marine crane, which is originally designed with boom length of 9 m. The study also examines whether scaled crane models may be used for experimental investigation of stress distributions by supporting FEM-based simulations to avoid expensive or difficult local and general testing procedures of the pre-designed cranes members.

MATERIAL AND METHOD

The Marine Crane and Its Solid Modelling

In the study, a sample marine crane, which is originally designed with the parameters of 9 m boom length and total boom structure weight of 1.33 Ton, is considered. The crane was reverse engineered based on original two-dimensional drawings and its solid model was created three-dimensionally. The solid model created has been scaled from 1:1 to 1:10. SolidWorks 3D Parametric Design Software was used for all solid modelling operations. The solid model has been used in the finite element analysis (FEA) and scaled prototype boom manufacturing processes. Description of the crane considered and its boom solid model can be seen in Figure 1.

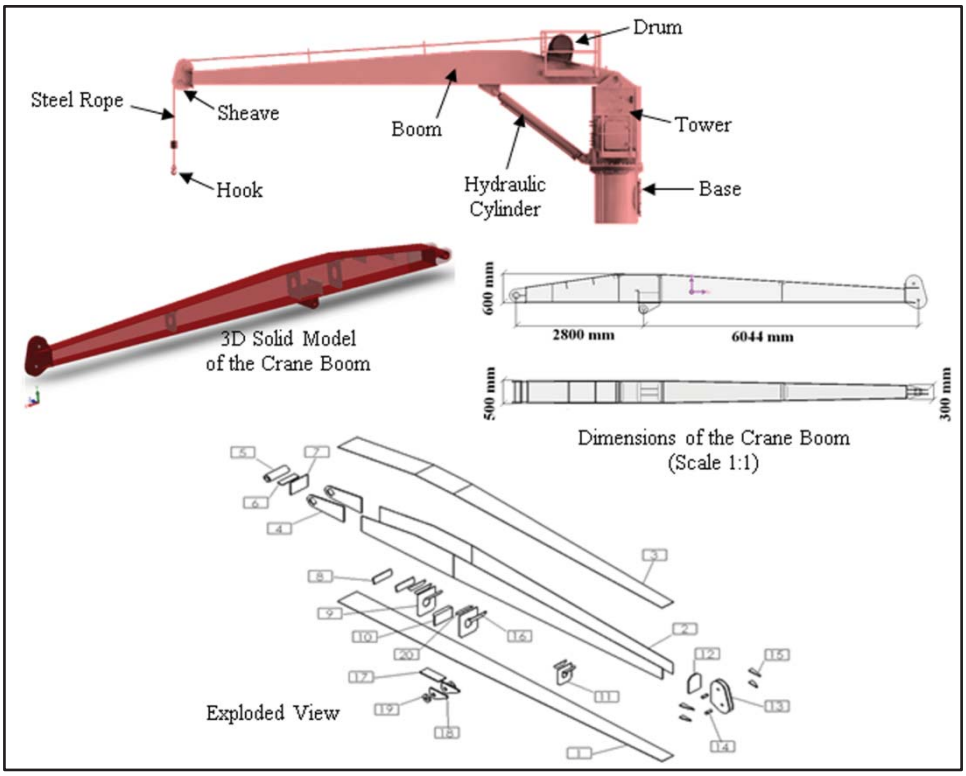


Figure 1. Crane's boom solid model and its general dimensions

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Stress Analysis of the Scaled Crane's Boom

Accurate measurement of strain, from which the stress can be determined, is one of the most significant predictors of product life (Lee et al, 2005). Probably the most ubiquitous and reliable of all the tools of experimental stress analysis is the electrical resistance strain gauge (Doyl, 2004). Therefore, the strain-gauge based experimental stress measurement technique is preferred in the experimental part of this study. If the components under stress evaluation have a complex shape or surfaces are too large to measure, the strain gauges may need to be applied to the component in critical locations. In the study, four strain-gauge locations were assigned to evaluate crane boom stress distributions for both applications: experimental and simulation. Two modules of QuantumX 840°A with 16 channels universal data acquisition system and 120 Ω, K-Y series $0^o/45^o/90^o$ rectangular three-element strain gauge rosettes from HBM have been utilised for the experimental data acquisition (HBM, 2012). In the study, as an important aspect of the full design analysis, only static loading condition with no wind loading case is considered in both the experimental and the simulation scenarios.

The scaled prototype crane's boom was placed onto a fixed platform and a tension adjuster was used to load the crane boom. A "S" type load cell of 50 kN capacity was placed between the crane boom sheave axle and tension adjuster using steel ropes for loading records. Simultaneous data acquisitions from strain gauges and load cell have been provided in the experimental study. The prototype scaled crane's boom was loaded until it reached plastic deformation failure, which was 20 loading steps in total. Experimental set up and locations of the placed strain gauges are given in Figure 2.

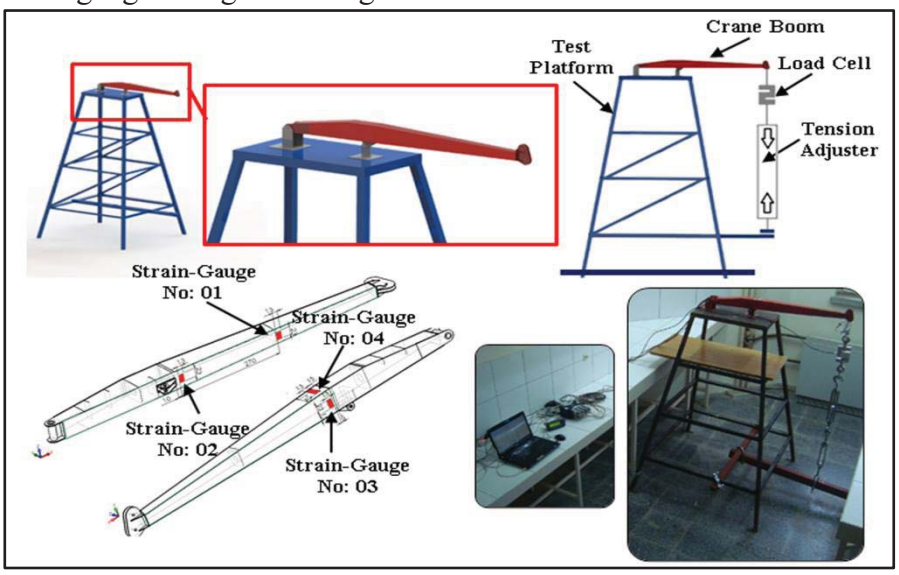


Figure 2. Experimental Set up

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At present, the FEM represents a most general analysis tool and is used in practically all fields of engineering analysis (Bathe, 1995). Ansys Workbench commercial finite element code was utilised for the FEM-based simulation part of this study. The FEA study was set up with 3D, static, linear and isotropic material model assumptions.Welding is one of the essential manufacturing methods used in the assembly operations of the steel based crane boom components. All stress analyses in this study were carried out considering bonded contact type assumptions and steel based material properties such as Young's Modulus of 210 GPa, Poisson Ratio of 0.3 and Density of 7850 kg m^{-3} (Kutay, 2003). Boundary conditions used in the FEA were defined considering the static loading case of the crane boom. The scaled crane boom was loaded from 100 N to 2000 N in 20 steps, that was until its failure in both the experimental and the simulation studies. Ansys Workbench meshing functions were used to create the finite element model of the crane boom (Ansys WB Doc., 2011). Meshing is one of the important steps to get accurate results from FEA, therefore it is wise to use a higher density mesh structure for the strain gauges locations on the crane boom solid model. Seven different types of quadratic elements, 113186 nodes and 43088 elements were obtained in total after the meshing operation. The defined boundary conditions and the mesh structure of the model are shown in Figure 3.

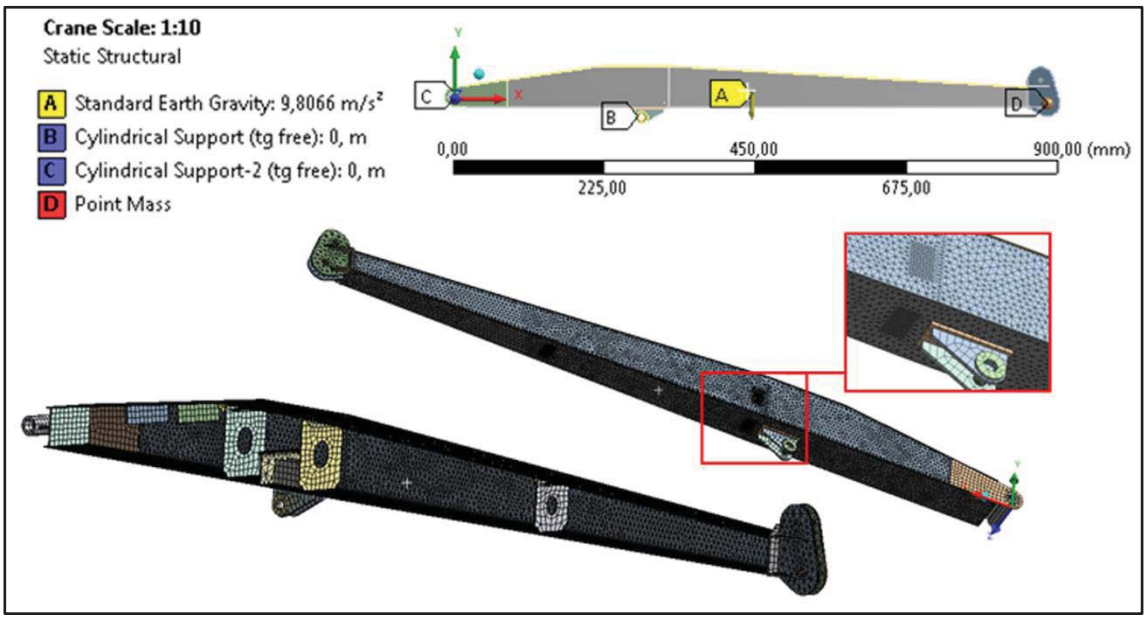


Figure 3. Boundary conditions and the mesh structure of the crane boom

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RESULTS and DISCUSSIONS

After all physical measurements and FEA solving processes, the results have been obtained and the data processed for the final evaluation. Simulation outputs gave a clear point of view to investigate stress distributions on the crane boom. As expected, maximum stresses appear at the boom's hydraulic cylinder linkage around the bottom plate of the boom framework. Sample screenprint images from the FEM code are given in Figure 4 to present stress distributions on the crane boom at the first loading step (loading magnitude of 100 N). As a crane boom design consideration, it can be commented that as is seen in Figure 4, stress distributions are quite well designed on the boom structure. Due to the linear assumption accepted within this study, it is believed that there would not be any change to the maximum stress location on the crane against the loading magnitude changes. Experimental data and the simulation results were processed from the pre-defined strain-gauge locations for comparison. All the processed data from the experimental study by comparing FEA results are given in Table 1 and the related charts are presented in Figure 5.

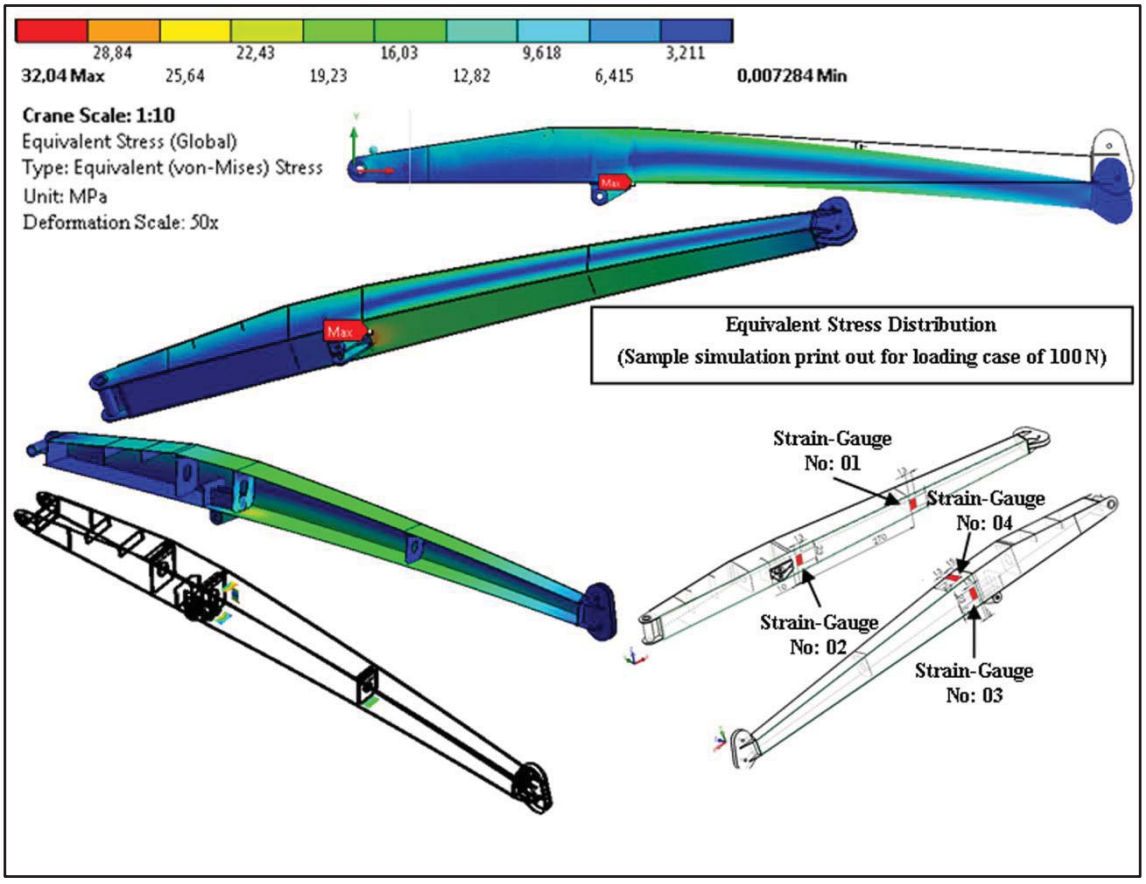


Figure 4.Stress distribution on the crane boom at the first loading step

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Table 1. Comparison of the stress magnitudes obtained from experimental and simulation operations

	Strain-Gauge No: 1			Strain-Gauge No: 2		
Applied Load (± 2) [N]	Experimental Study (ES) [MPa]	FEA [MPa]	Error [(ES-FEA)/ES] [%]	Experimental Study (ES) [MPa]	FEA [MPa]	Error [(ES-FEA)/ES] [%]
100	16.55	15.18	8.29	25.77	22.87	11.24
200	29.40	30.05	2.21	38.88	45.00	15.74
300	41.30	44.92	8.77	55.38	67.13	21.21
400	53.66	59.79	11.43	69.94	89.25	27.61
500	66.73	74.66	11.89	87.23	111.38	27.68
600	78.84	89.54	13.57	105.33	133.50	26.75
700	91.50	104.41	14.11	118.60	155.63	31.22
800	103.40	119.28	15.36	136.49	177.76	30.23
900	116.50	134.15	15.15	152.80	199.88	30.81
1000	129.90	149.02	14.72	171.30	222.01	29.60
1100	141.70	163.89	15.66	191.00	244.14	27.82
1200	154.20	178.76	15.93	208.36	266.26	27.79
1300	166.53	193.64	16.28	223.55	288.39	29.00
1400	179.40	208.51	16.23	236.14	310.51	31.50
1500	192.20	223.38	16.22	256.87	332.64	29.50
1600	204.10	238.25	16.73	266.72	354.77	33.01
1700	216.90	253.12	16.70	81.55	376.89	362.16
1800	230.20	267.99	16.42	2010.00	399.02	80.15
1900	242.10	282.87	16.84	1522.00	421.14	72.33
2000	248.40	297.74	19.86	1438.00	443.27	69.17

	Strain-Gauge No: 3			Strain-Gauge No: 4		
Applied Load (± 2) [N]	Experimental Study (ES) [MPa]	FEA [MPa]	Error [(ES-FEA)/ES] [%]	Experimental Study (ES) [MPa]	FEA [MPa]	Error [(ES-FEA)/ES] [%]
100	6.51	4.99	23.37	26.56	16.77	36.86
200	11.35	7.81	31.16	47.15	33.02	29.97
300	15.87	11.64	26.66	66.50	49.27	25.91
400	20.55	15.46	24.75	85.48	65.52	23.35
500	25.46	19.29	24.24	106.80	81.77	23.43
600	30.17	23.11	23.39	126.70	98.03	22.63
700	35.24	26.94	23.56	146.80	114.28	22.15
800	39.56	30.76	22.23	166.10	130.53	21.42
900	44.89	34.59	22.95	185.80	146.78	21.00
1000	51.06	38.41	24.77	207.40	163.03	21.39
1100	55.91	42.24	24.45	225.60	179.28	20.53
1200	67.74	46.06	32.00	244.80	195.53	20.13
1300	73.72	49.89	32.32	264.70	211.78	19.99
1400	79.12	53.72	32.11	303.10	228.03	24.77
1500	85.41	57.54	32.63	322.50	244.29	24.25
1600	92.95	61.37	33.98	343.20	260.54	24.09
1700	117.10	65.19	44.33	373.40	276.79	25.87
1800	228.70	69.02	69.82	398.60	293.04	26.48
1900	1284.10	72.84	94.33	1048.40	309.29	70.50
2000	1369.20	76.67	94.40	1532.00	325.54	78.75

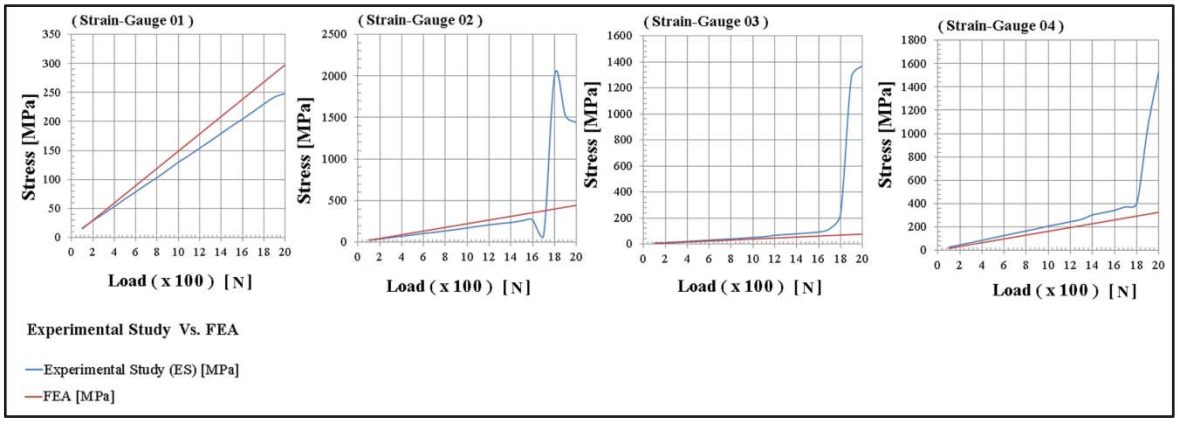


Figure 5. Comparison charts for stress magnitudes (Experimental vs. FEA)

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However, an increase for the differences can be seen between the experimental and simulation values over time, and as such, the charts given in Figure 5 show that there is a correlation between the experimental and the simulation values in a linear perspective.

The boom was loaded until its plastic deformation failure point and the information obtained from the experimental part of the study showed the deformation locations of the boom proved visually that the strain gauges were quite well located to gather information about the critical stress points (Figure 6). Physical deformations on the boom can quite clearly be seen at the location of strain gauge no 2 and no 3. Similarly, it can be commented that deformation at the location of strain gauge no 1 and no 4 is not clear as much as the others because the tensile and compression directions and load effect are not enough for more bending or buckling cases. Beside this, after load step 16, plastic deformation cases can be seen clearer in the charts belonging to strain gauge no 2, no 3 and no 4.



Figure 6. Plastic deformation shapes of the boom

CONCLUSIONS

Stress analysis of a sample scaled marine crane's boom under static loading condition is discussed as the detail of this study. To investigate stress distributions on the crane boom, experimental and FEM-based simulation techniques have been used and the results obtained from both have been compared. Some points can be summarised as follows:

1. The crane design, manufacturing, design validation and testing procedures are long processes; this study pointed a way that can be useful to have an idea about full size design validation / testing of the crane boom under static loading conditions using both stress analysis techniques (these being strain measurement and FEM based simulations).

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2. FEM based simulations are important in design to assure that the crane is fit for purpose and fulfil the design requirements. Furthermore, it can be used to optimise the mechanical and geometrical design features of the cranes.
3. One of the supplementary studies for the FEM-based simulations is to generate an experimental study. In the study, a correlation between experimental and simulation results is obtained, however an increase was observed between results against rising load magnitudes.
4. In addition to the important stress distribution visualisation from the FEM based results, physical deformation shapes obtained from the experimental study can give more vital information during crane design decision steps.
5. The methodology used in this study can also be used for similar types with different sized crane boom analysis. So designers could find opportunity to test their design with no lost time.
6. For future work, it is planned to undertake a detailed research to obtain an empirical approach to determine the relationship between the scaled and full size crane boom maximum safe loading magnitudes which is also a design criteria of the marine cranes.

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