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Original Article

A Case Study on Engineering Failure Analysis of Link Chain

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Objectives: The objective of this study was to investigate the effect of chain installation condition on stress distribution that could eventually cause disastrous failure from sudden deformation and geometric rupture.
Methods: Fractographic method used for the failed chain indicates that over-stress was considered as the root cause of failure. 3D modeling and finite element analysis for the chain, used in a crane hook, were performed with a three-dimensional interactive application program, CATIA, commercial finite element analysis and computational fluid dynamic software, ANSYS.
Results: The results showed that the state of stress was changed depending on the initial position of the chain that was installed in the hook. Especially, the magnitude of the stress was strongly affected by the bending forces, which are 2.5 times greater (under the simulation condition currently investigated) than that from the plain tensile load. Also, it was noted that the change of load state is strongly related to the failure of parts. The chain can hold an ultimate load of about 8 tons with only the tensile load acting on it.
Conclusion: The conclusions of this research clearly showed that a reduction of the loss from similar incidents can be achieved when an operator properly handles the installation of the chain.

Key Words: Chain safety, Fractographic analysis, Finite element analysis, Industrial accident

Introduction

Industrial disasters have increased in proportion to the development of industry. While industrial disasters in our country have decreased annually, the rate of our disasters is still higher than that of industrially advanced nations [1]. Various efforts are needed to reduce industrial disasters. Four major phenomena, including insertion/winding, conduction, falling and collision, should be thoroughly studied because they account for 62.3 percent of all industrial disasters [2] that are classified by failure mode. It is reported that disasters are more likely to occur when the operator does not follow proper procedures.

In this study, 3-dimensional (3D) modeling and FE analysis were performed to identify the correct and incorrect installation procedures of link chain, and identify factors which could lead to disastrous failures from the incorrect installation. A chain (Fig. 1), consisting of consecutively connected metal rings, is usually used to crane heavy weight materials and hot parts in industry, due to its rigidity and strong resistance to heat and corrosion [3]. The results show that a method to reduce the rate of disasters could be identified by quantifying the effect of the worker's incorrect handling of the chain link procedure.

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Fig. 1. Chain specimen of original crane chain.

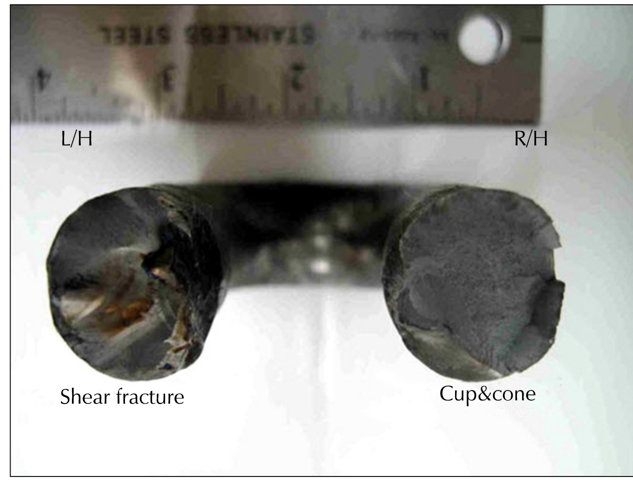

Fig. 3. Photographs of normal crane chain.

Fig. 2. Failed crane chain.

Materials and Methods

This study utilized 3D modeling and finite element analysis [4-6] of the chain which is used in the crane to estimate the effect of different load cases on structural rigidity. CATIA [7], three-dimensional interactive application program was used for 3D modeling of the chain and ANSYS [8-11], commercial finite element analysis software was used for this analysis.

Fractographic analysis

Before performing stress analysis for crane chain, observation of the fracture surface of the failed chain was conducted in order to understand the possible failure mechanism. This procedure helped us to identify the guideline to further analyze the failure mechanism mainly in two conditions which are discussed in detail in the following section.

After failure of the crane chain occurred, a fractured chain was sent to a metallurgical laboratory to identify the failure mechanism and its root cause. As shown in Fig. 2, the width of the ruptured chain ring was shrunk by deformation when the chain failed, without retaining its original shape. The fracture surface which was formed at an angle of 30-45° to the primary load direction, clearly shows the shear fracture. In a macroscopic view, both fracture surfaces of the crane chain show a shear fracture (Fig. 3 L/H) and the cup and cone shape (Fig. 3 R/H), of which phenomena are considered as evidence of catastrophic failure due to improper overload. Especially, Fig. 3 L/H shows a shear fracture with crushed damage formed by the compressive load on the side of the chain. To analyze the fracture surfaces, each part was viewed with a scanning electron microscope. As shown in Fig. 4, the fracture surface having the shape of cup and cone as an enlarged area of Fig. 3 R/H shows the equiaxed dimples in the flat surface and the elongated dimples in the inclined region. Elongated or equiaxed dimples are observed inside the fracture surface. Fig. 4B and 5C show the step-like topographies indicating the fracture due to bending moment rather than uniaxial tension. Also, as shown in Fig. 4D, cleavage fracture surface is usually formed under high strain rate loading condition. Therefore, it is considered that the fracture of the crane chain was occurred under high strain rate bending moment rather than uniaxial tension instantaneously.

FE modeling and material

A quarter model of the chain's configuration was generated

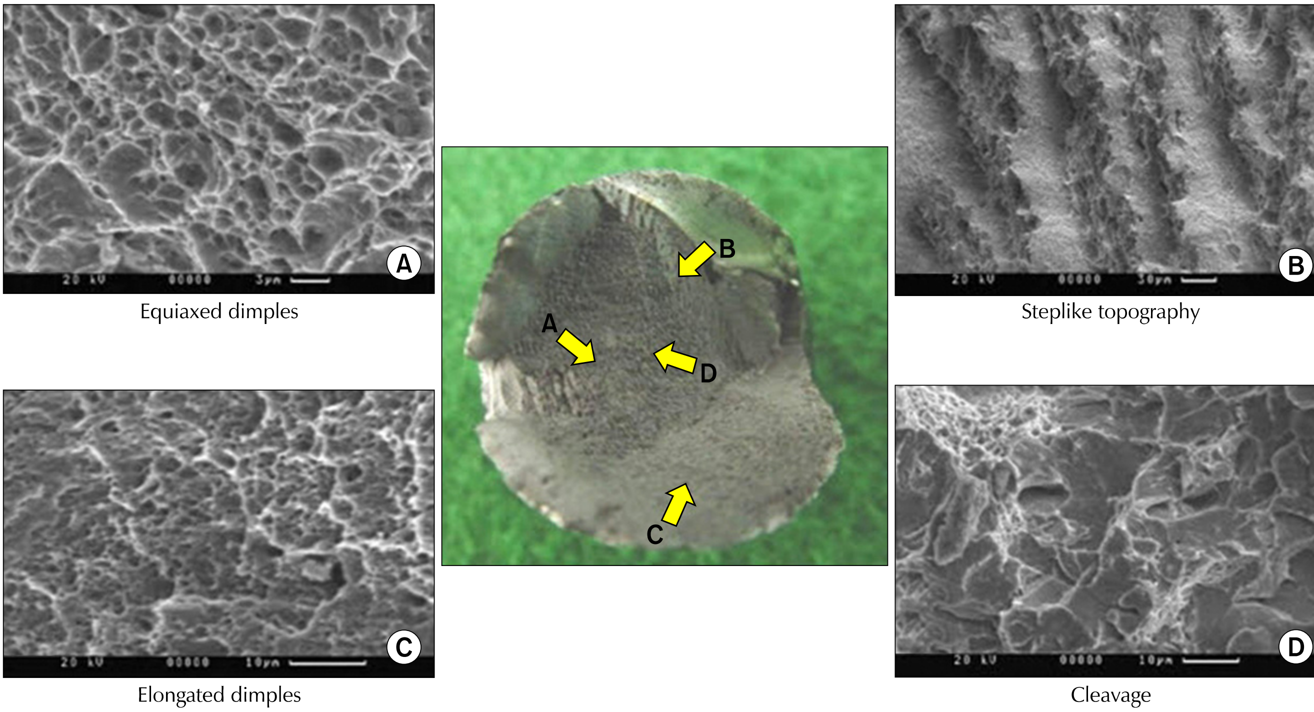

Fig. 4. Higher-magnification view of fracture surfaces (Fig. 3 R/H) reveal dimple rupture.

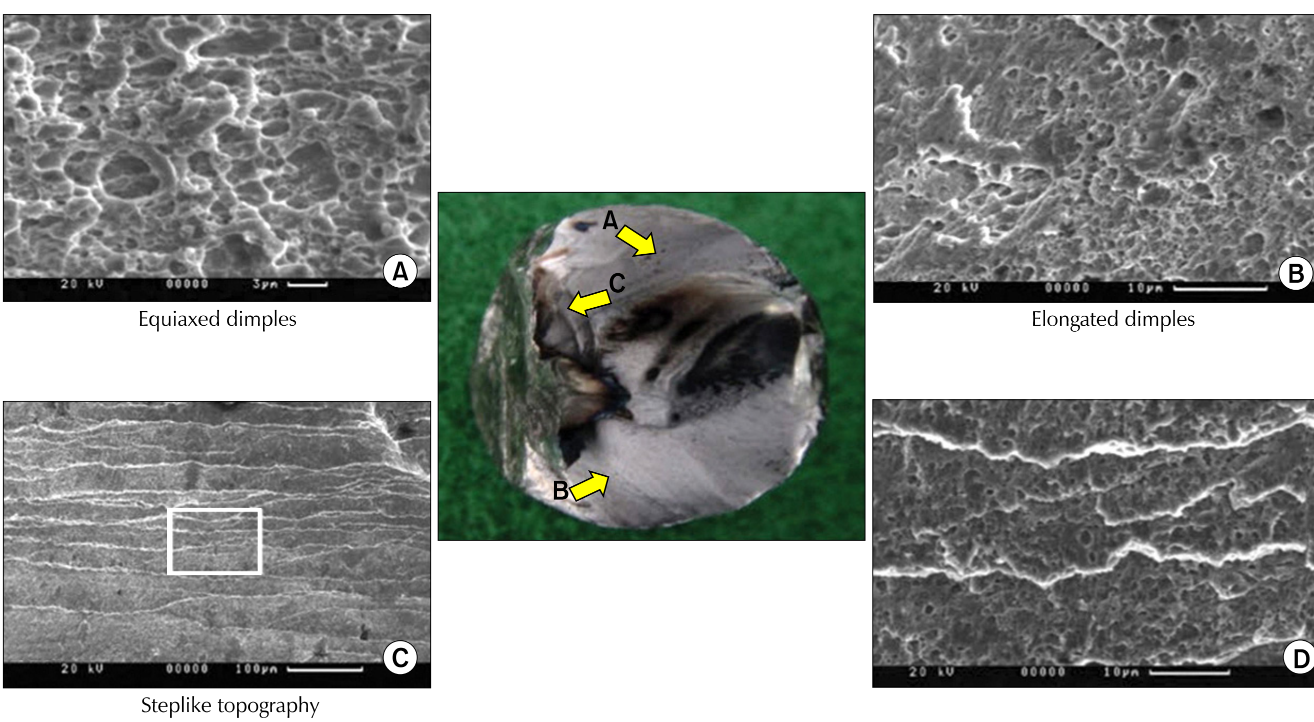

Fig. 5. Higher-magnification view of fracture surfaces (Fig. 3 L/H) reveal dimple rupture and step-like topography formed by overload.

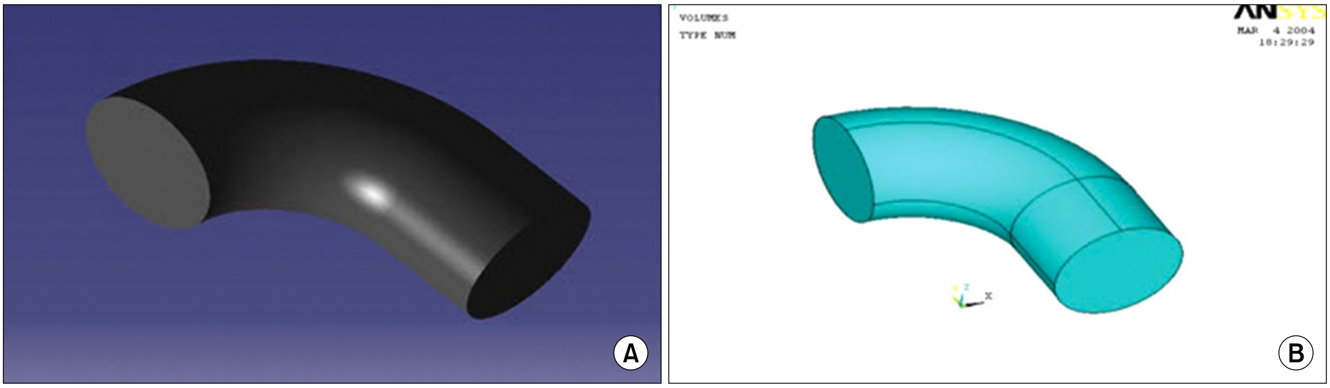

Fig. 6. Three-dimensional (3D) models of crane chain. (A) 3D model generated in CATIA. (B) 3D model imported in ANSYS model.

by CATIA, because the dimension of the crane chain is symmetrical with respect to longitudinal and horizontal axes. A cross sectional area of the chain was assumed to be constant, without considering the irregularities of the welding zone. The quarter model of the crane chain generated in CATIA and input to ANSYS for the analysis is shown in Fig. 6. The number of nodes and elements used for a quarter of the FE chain model are shown in Table 1.

Results of chemical analysis in Table 2 show that the material of the crane chain is American Iron and Steel Institute (AISI) 8622 steel. The chain made of AISI 8622 steel has a yielding strength of 805 MPa, an ultimate strength of 1204 MPa, an elastic modulus of 205 GPa, and a Poisson's ratio of 0.25. The material properties of AISI 8622 steel are also shown in Table 3.

Table 1. The number of nodes and elements

	ANSYS
Node	1,800
Element	1,463

Analysis condition and method

The failure of the crane chain attached to the hook occurs under the influence of a mixture of various excessive loads. Furthermore, the residual stress is also generated in the welding zone of the chain because the temperature gradient and thermal stress were formed by irregular heating during the welding process [12].

This study did not deal with the surface fatigue cracks initiated by the result of long-term usage and surface defects, which accounted for about 60-70 percent of the causes of machine element failure [13]. Due to absence of a fatigue test machine for chain, the current study concentrated on the simple two load conditions, tension and bending, that could occur depending on the installation condition of the hoisting hook which is demonstrated in Fig. 7 [14]. In this research, FE analyses for the chain were performed when the tensile and bending load were acting on it with the symmetric state as the boundary condition. Fig. 7A is the properly installed connecting chain which is linked up with the hoist hook. On the other hand, Fig. 7B shows the improper installation of a smaller chain whose outside surface is directly contacting the hoist hook.

A symmetrical boundary condition was applied in the FE model with one quarter of the chain configuration. The section area suffered loads is subjected to a symmetry boundary condition, namely displacement of vertical direction on area is zero. The other one is zero displacement in DOFs. The analysis was conducted under the various load conditions with the magnitude acting on the cross section of the chain. The applied boundary and load conditions of the crane chain are shown in Figs. 8 and 9.

Results and Discussion

Analysis with respect to load state

Using the ANSYS FEA software, we calculated the stress distribution under the condition that the axial tensile load acts on the chain. Also, the stress distribution was analyzed when the bending load was applied to the chain. Fig. 10 shows the results of the ANSYS analysis when tension is applied.

Fig. 11 shows the results of the ANSYS analysis when a bending load is applied. From the numerical analysis, the results show that the maximum Von-Mises stress is 455 MPa from ANSYS under axial tension. When the bending moment is applied, the stress is 1,236 MPa. Considering the case of

Table 2. Chemical analysis of failed crane chain

Compartment	Composition of chemical (%)									
	C	Si	Mn	P	S	Ni	Cr	Mo	Cu	Fe
SPEC (AISI 8622)	0.20-0.25	0.15-0.35	0.70-0.90	Less than 0.035	Less than 0.040	0.40-0.70	0.40-0.60	0.15-0.25	-	Rest
Crane chain	0.244	0.160	0.758	0.011	0.007	0.537	0.332	0.174	0.081	Rest

AISI: American Iron and Steel Institute.

Table 3. Mechanical properties of failed crane chain

Material	Tensile strength	Yield strength	Elongation	Hardness	Remarks
AISI 8622	1,204 MPa	805 MPa	11.3%	HRC 40	Low carbon alloy

AISI: American Iron and Steel Institute, HRC: Rockwell hardness C scale.

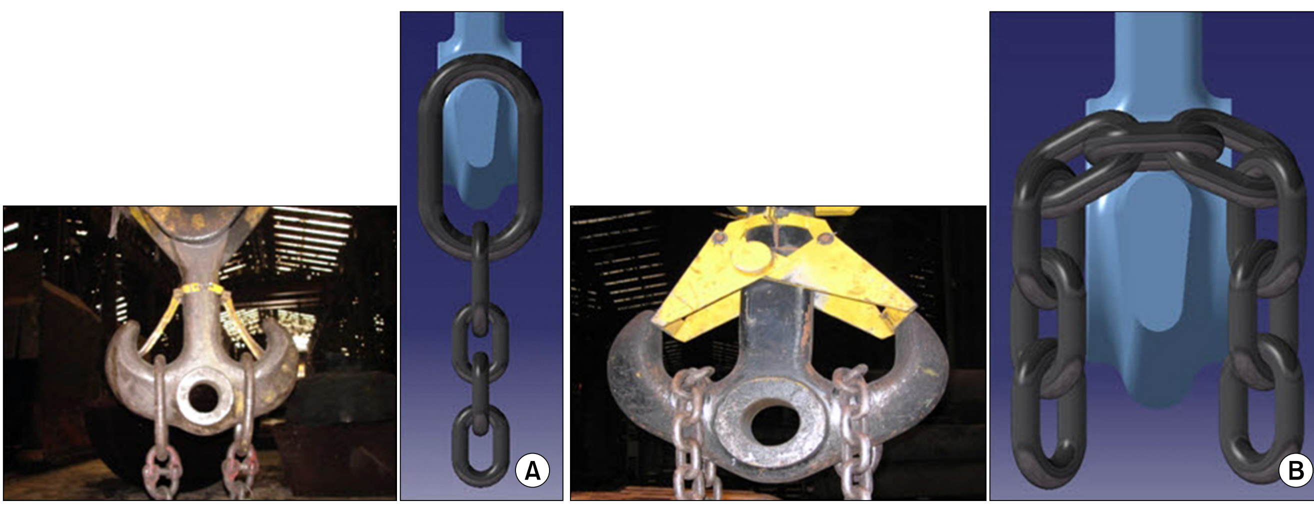

Fig. 7. The state of loading condition with respect to the installation of crane chain. (A) Correct installation: tension load. (B) Incorrect installation: bending load.

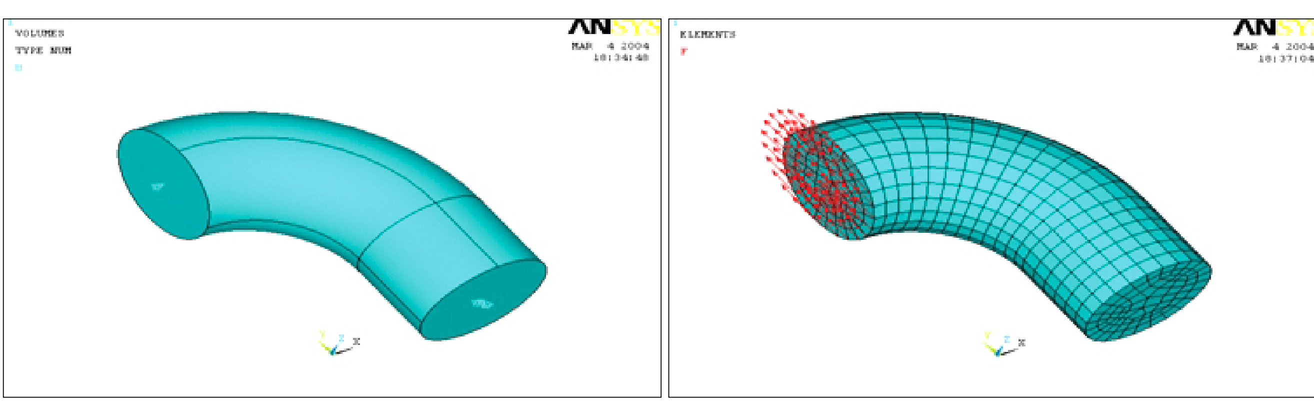

Fig. 8. Boundary and tension load condition for FE crane chain model.

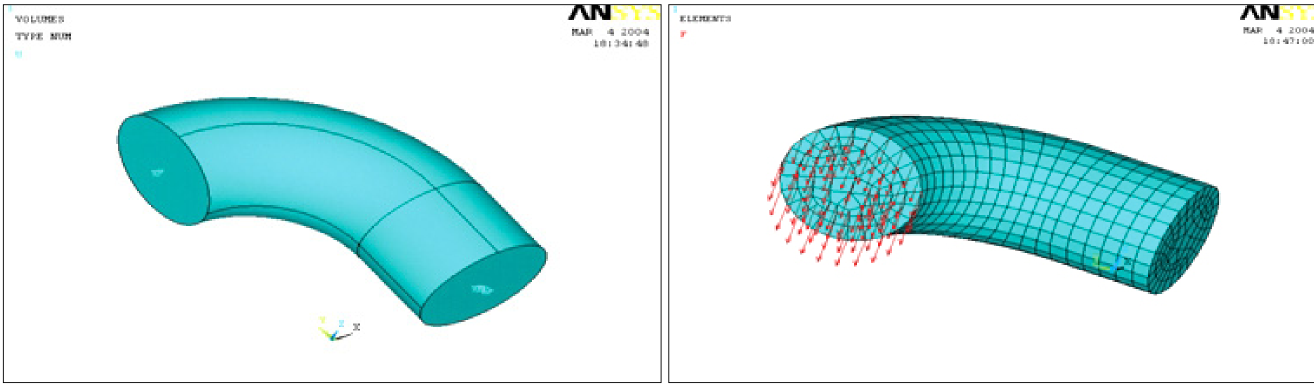

Fig. 9. Boundary and bending load condition for FE crane chain model.

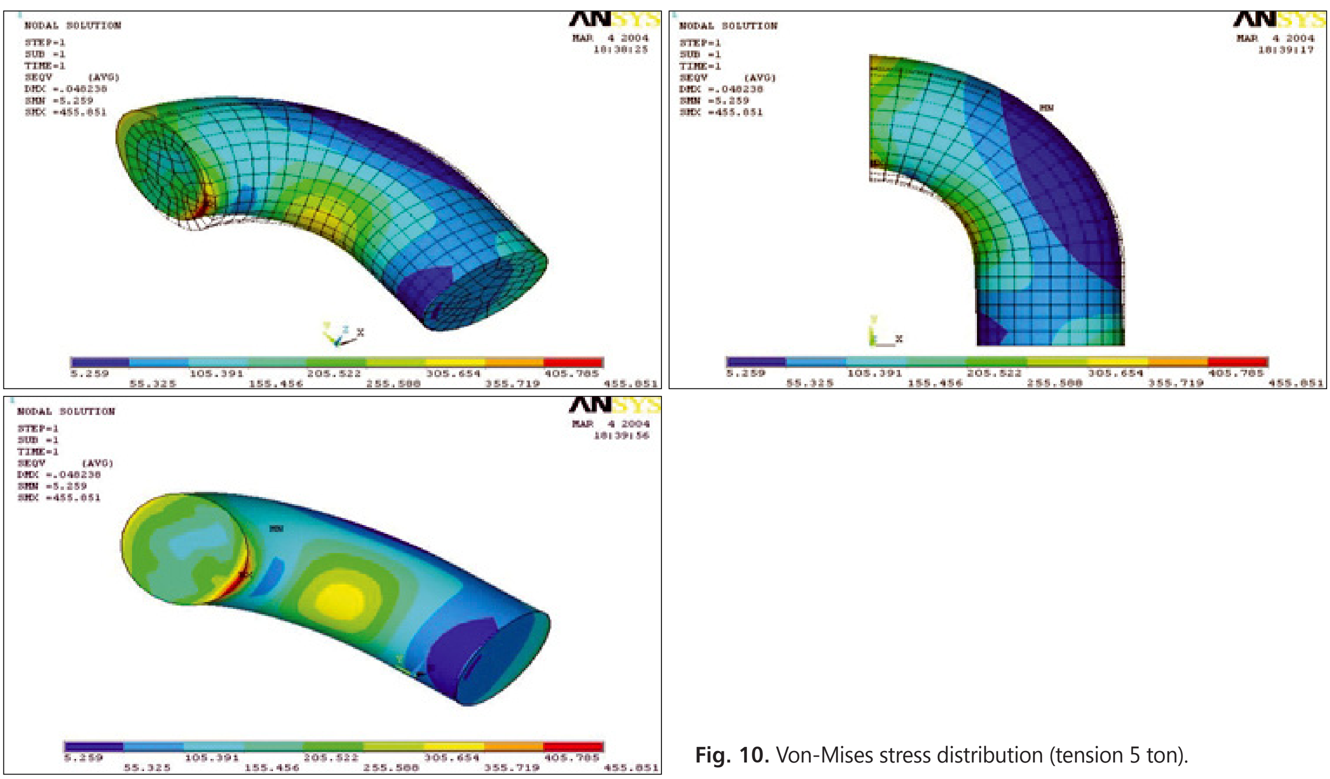

Fig. 10. Von-Mises stress distribution (tension 5 ton).

five tons of tensile load, the analysis result computed from FE analysis is approximately 460 MPa, which is lower than that of the yield strength of the material. On the contrary, when five tons of bending load is applied, the result amounts to approximately 1,180 MPa, nearly reaching the ultimate strength (1,204 MPa). Also the result shows that the stress magnitude occurred by a bending force is 2.5 times greater than that of a plain tensile load. From the results, we are sure that the magnitude of stress is heavily dependent on the stress state acting on the fracture surface.

Material properties of chain

Results of chemical analysis and a hardness test show that the failed chain was an AISI 8622 steel alloy. Chemical analysis and mechanical properties of the failed crane chain are summarized in Tables 2 and 3. In this alloy, nickel in combination with chromium, produces low-alloy steel with higher elastic limits, greater hardening capability, and higher impact and fatigue resistance than plain-carbon steel. The further addition of about 0.2% Mo increases hardening capability even more and minimizes the susceptibility of these alloys to temper embrittlement. This alloy is used for shafts

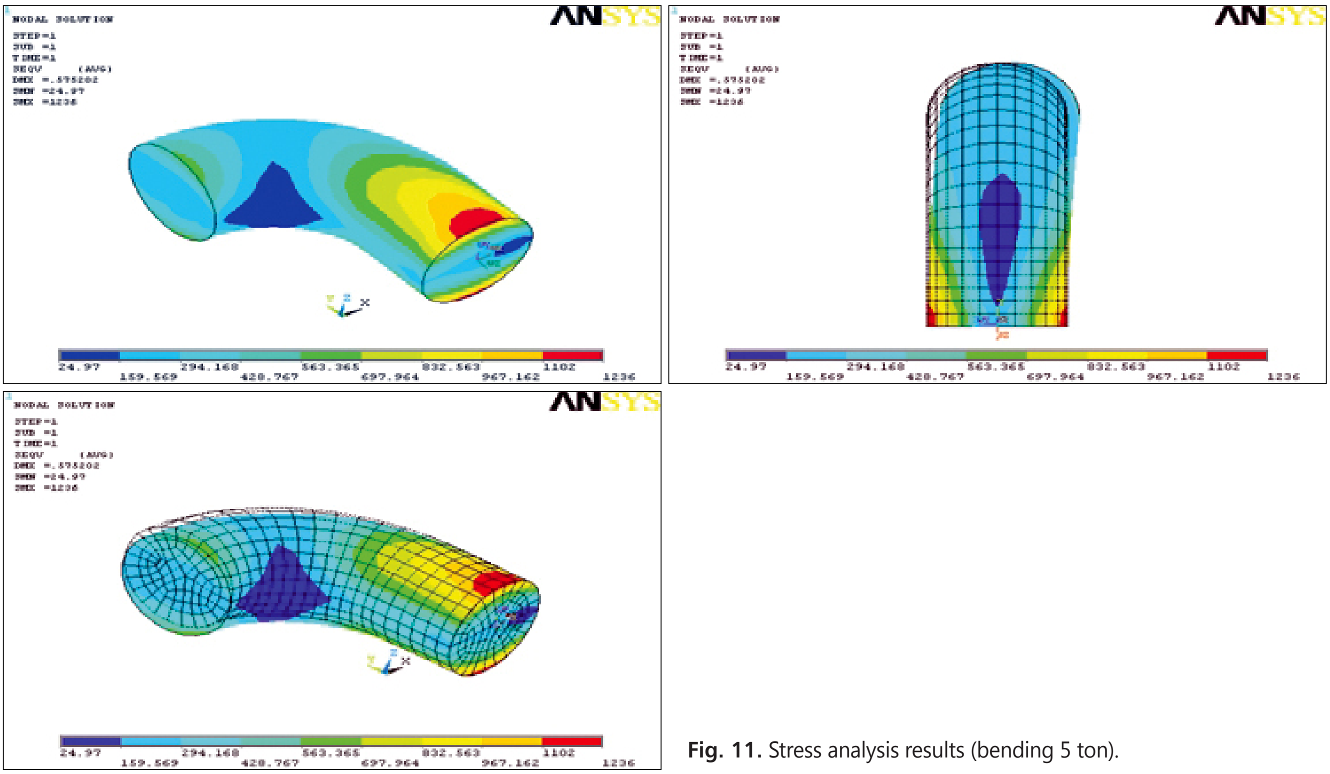

Fig. 11. Stress analysis results (bending 5 ton).

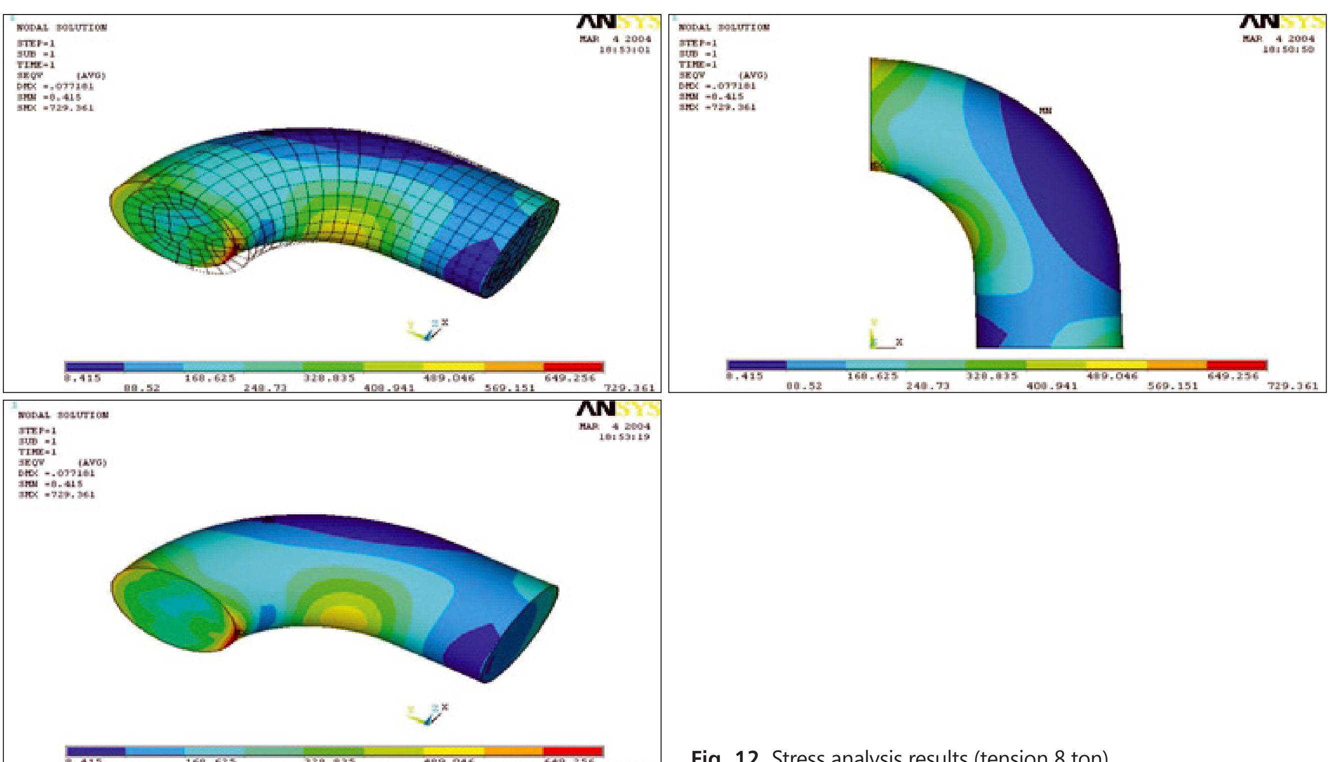

Fig. 12. Stress analysis results (tension 8 ton).

and many other applications in forgings which require high strength.

Maximum allowable load

From the experimental simulations conducted with respect to various load cases, it was found that the chain can hold an ultimate load of about 8 tons when the tensile load acts on it as shown in Fig. 12. In this case, the maximum Von-Mises stress amounts to 729 MPa in ANSYS, which is slightly lower than that of the yield strength (805 MPa) of the material, AISI 8622 steel.

Conclusions

In this research, structural safety of a crane chain was investigated through the prediction of the chain's material behavior and the calculation of maximum allowable load with respect to tension and bending loads. The results are summarized as follows.

1) The fractographic analysis of the failed part reveals that the crane chain was fractured catastrophically by the bending forces.
2) The results of finite element analysis show that the state of stress is strongly affected by the condition of the chain installed in the hook, due to the fact that the stress magnitude caused by bending forces is 2.5 times greater than that of the plain tensile load.
3) FEA results are in accordance with the fractographic analysis, in that the change of load condition from tension to bending severely affects the failure of parts.

Furthermore, detailed analysis is recommended to consider residual stress in the welding zone and various changes of load condition in order to further refine the fracture mechanism analysis.

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