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Failure Analysis of fractured Fixing Bolts of a Mobile Elevating Work Platform using Finite Element Methods

Abstract

Mobile elevating work platforms (MEWPs) consist of a work platform, extending structure, and chassis, and are used to move persons to working positions. MEWPs are useful but are composed of pieces of equipment, and accidents do occur owing to equipment defects. Among these defects, accidents caused by the fracture of bolts fixed to the extension structure and swing system are increasing. This paper presents a failure analysis of the fixing bolts of MEWP. Standard procedure for failure analysis was employed in this investigation. Visual inspection, chemical analysis, tensile strength measurement, and finite element analysis (FEA) were used to analyze the failure of the fixing bolts. Using this failure analysis approach, we found the root cause of failure and proposed a means for solving this type of failure in the future. First, the chemical composition of the fixing bolt is obtained by a spectroscopy chemical analysis method, which determined that the chemical composition matched the required standard. The tensile test showed that the tensile and yield strengths were within the required capacity. The stress analysis was carried out at five different boom angles, and it was determined that the fixing bolt of MEWP can withstand the loads at all the boom angles. The outcomes of the fatigue analysis revealed that the fixing bolt fails before reaching the design requirements. The results of the fatigue analysis showed primarily that the failure of the fixing bolt was due to fatigue. A visual inspection of the fractured section of the fixing bolt also confirmed the fatigue failure. We propose a method to prevent failure of the fixing bolt of the MEWP from four different standpoints: the manufacturer, safety certification authority, safety inspection agency, and owner.

Keywords: Fatigue Analysis, Finite Element Analysis(FEA), Mobile Elevating Work Platforms(MEWPs), Fixing bolt

1. Introduction

A mobile elevating work platform (MEWP) is a machine used for mobility. It moves persons to working positions where they can carry out their work from the work platform, with the intention that the workers board and disembark from the platform only at access positions at the ground level or on the chassis. At a minimum, the MEWP consists of a work platform with controls, an extending structure, and a chassis [1]. MEWP saves time and makes work at height efficient, effective, and safer than using traditional methods of access. The use of MEWPs is increasing as the benefits for productivity and safety are recognized. However, the increased use of MEWPs in construction, maintenance, and other applications where trapping risks are present has led to accidents in which people on the platform have been trapped between the platform (often referred to as a cage or basket) and objects in the work area. In some cases, these accidents have involved fatalities [2].

In Korea, unfortunately, a significant number of accidents involving the use of MEWPs have occurred over the past 10 years, including tragic fatalities (Table 1). The number of accidents caused by mechanical defects is 42, and those caused by fixing bolt defects is 9, which is 21% of the total (Table 2) [3].

The failed MEWP of this study consists of a middle frame, X-shape front outrigger, rear outrigger, turntable, 6-stage boom, one boarding work platform, and derrick cylinder, as shown in Fig. 1. The main composition has various functions, such as left-right 360° operation (boom rotation), withdrawal, and lead-in operation. These functions deal with the producer of oil pressure power, which contains the oil pump and system. . The turntable was jointed symmetrically to the swing system and post base by twenty M16 bolts of property class 10.9.

Out of these 20 bolts, 4 bolts were fractured [Fig. 2]. According to the information from the customer, this MEWP failed after 40 months of service [Fig. 3]. Notably, none of the four fractured bolts were accessible, and only one bolt (R10), which received the most loading, was studied.

Several studies have been reported in the literature regarding the fracture of fixing bolts in different engineering systems [4-9]. For example, in one of these case studies [4], addressing the co-fracture of 16 connecting bolts of a filter press cylinder-piston system, it was concluded that the bolts had failed owing to fatigue, apparently the result of insufficient torque used during assembly. In another investigation [5], the fracture of worm-gear connecting bolts, due to two-way bending fatigue, was reported. The main reason for the fracture was the large gap between the bolts and their matching internal gear bolt holes, resulting from component wear.

Accordingly, failure analysis of the fractured fixing bolts to prevent similar failure accidents was the main aim of the present study. Visual and material inspection, fracture mechanics, and finite element analysis (FEA) of structure and fatigue were used to determine the main causes and mechanisms of failure [6].

2. Methods

To evaluate the material composition and mechanical properties of the fractured fixing bolts of a MEWP, the mandatory tests of ISO 898-1 class 10.9 standard were performed [10]. For this purpose, atomic absorption spectroscopy and tensile tests were performed according to the ASTM E415 and ASTM A370 standards, respectively. The strength was measured according to the instrumental indentation technique (using AIT-U made by FRONTICS) and the chemical composition was determined by a spectroscopy chemical analysis method (using ARL iSpark 8880 made by Thermo Scientific).

Three-dimensional (3-D) finite element analysis (FEA) has been widely used for the quantitative evaluation of stress in the critical zones of a structure. Therefore, in this study, a well-known solid modeling software, SOLIDWORKS 2016 × 64 Edition, was used to design the parts of the MEWP. Afterwards, these parts were imported to ANSYS 17.1 in the SLDPRT format file. Finally, finite element modeling was proposed, and structural analysis and fatigue analysis were performed simultaneously for the fixing bolts of the MEWP.

3. Results and discussion

3.1. Physical testing and chemical analysis

3.1.1. Visual inspection

A visual inspection of the fractured section of the fixing bolt (R10) in the turntable revealed characteristics of a fracture at the bolt thread near the contact part of the post base and swing system. The fatigue crack appears to have propagated to the center of the bolt starting from the thread, revealing three typical characteristics of fatigue failure—a smooth fatigue zone, rough fatigue zone, and overload or final fracture zone at the fracture plane [5-7]. A schematic of the fractured fixing bolt with specific zones is illustrated in Fig. 4.

3.1.2. Chemical compositions analysis

Chemical composition analysis of the fractured fixing bolts was performed, and the results are listed in Table 3 [8-9]. All the element properties of the bolts meet the technical requirements of the class 10.9 standard.

3.1.3. Tensile test

The tensile test results are presented in Table 4. The permissible values of ISO 898-1 for class 10.9 mechanical properties are also included in this table [10]. In this regard, the tensile test results are compatible with the class 10.9 standard [11].

3.2. Finite element model and boundary condition

3.2.1. Modeling

In this study, the height of the MEWP is 2985 mm, and it is equipped with a telescopic boom of 16,000 mm maximum withdrawal when the boom angle is 0° and 28,000 mm when the boom angle is 80° [12]. For structural and fatigue analysis of the turntable fixing bolts, as shown in Fig. 5, a 3D model consisting of a swing system, post, and booms 1–6 was modeled by SolidWorks. The 3D model was in the form in which the boom angle was increased by 20° intervals from 0° to 80° within the working radius of the MEWP.

3.2.2. Mesh

To simplify the 3D shape for mesh work, unnecessary weld structures attached to the post were removed, and mesh operations were performed. The type of element used is a tetrahedral element, and the number of nodes and elements of the model according to each boom angle are shown in Table 5, with the finite element model shown in Fig. 6.

Among the components that make up the MEWP, the material of the pins and bushing are SM45C, post base is SS400, booms 1–6 and the post are ATOS80, the fixing bolts are S45C, the swing system is S48C, and the derrick cylinders are STC60. The properties of the material are shown in Table 6 [13-15].

3.2.3. Boundary conditions

The load conditions are as follows. First, the bolt was torqued to the head of the bolt to tighten the bolt; thus, a pretension value of 105,000 N was applied to the side of the bolt [16]. Second, the maximum load (3.9 kN) and the load of the workplatform (1.7 kN) was placed in the direction of gravity at the end of boom 6. Finally, the gravity of the earth was considered [17].

The boundary conditions of the structural analysis are shown in Fig. 7. The fixed support at the lower end of the swing system was bonded to the post base, each boom and the corresponding bolt head were bonded to the post base, the post base was bolted to the swing system without separation, and the bolt side was bonded to the swing system, which was fully engaged with thread. Each joint and pin served as a cylindrical support with a fully fixed radius and axial direction, and the tangential direction was free [18].

For the fatigue analysis, the load condition and boundary condition were the same as those in the previous structural analysis, and the S-N curve information of the fixing bolt (S45C) for fatigue analysis was input in addition to the material properties [19-20]. The cyclic load consisted of a sine-type zero-based load, and Goodman's fatigue equation was applied [21-24]..

3.2.4. Result of structural analysis

The maximum von-Mises equivalent stress acting on the fixing bolt (R10) was obtained by increasing the boom angle from 0° to 80° by 20° intervals according to the maximum work radius of MEWP. The results of the structural analysis are shown in Fig. 8. The maximum von-Mises equivalent stress is between 550.8 MPa and 553.35 MPa. These values are less than the yield strength of fixing bolt, 1132 MPa, and the safety factor is 2.05, which is greater than the MEWP design safety factor of 1.48 [25], confirming that the fixing bolt was designed safely.

3.2.5. Result of fatigue analysis

The finite element code of ANSYS Workbench was used to obtain the fatigue life, safety factor, and damage distribution on the fixing bolt.

Fig. 9 represents the available life (number of cycles under constant loading conditions before the fixing bolt fails owing to fatigue) for the given fatigue analysis. As the figure shows, the minimum life (between 77,589 cycles and 83,443 cycles) has been determined for the zone with the maximum von-Mises equivalent stress of the fixing bolt.

Fig. 10 indicates the fatigue damage, which is defined as the design life divided by the available life. As this figure shows, the maximum damage (between 1.19 and 1.29) occurs at the critical zones (a value greater than 1 indicates that the fixing bolt will fail from fatigue before the design life is reached).

Fig. 11 represents the factor of safety (FS) with respect to fatigue failure at a given design life. This value is valid between the minimum safe zones (0) and maximum safe zones (15). As this figure shows, the minimum safety of the design (between 0.98 and 0.98516) designates the critical zones.

4. Conclusions

The failure analysis of the fixing bolt of MEWP was investigated by visual inspection, chemical composition analysis, tensile strength measurements, and FEA. The following conclusions were drawn from the study.

1. The chemical composition of the fixing bolt was examined by the spectroscopy chemical analysis method, which found that the chemical composition matched the required standard.
2. The tensile test revealed that the tensile and yield strengths were within the required capacity.
3. The stress analysis carried out at five different boom angles determined that the fixing bolt of the MEWP can withstand the loads at all the boom angles. The results indicate that the stresses in the fixing bolt are well within the safety limits, with a safety factor of 2.05.
4. The outcomes of the fatigue analysis revealed that the fixing bolt fails before reaching the design requirements (fatigue life $\geq$ 100,000 cycles, safety of factor $\geq$ 1.0, damage $\leq$ 1.0) [26], and the failure process (crack initiation – crack propagation – fracture) starts at the zone with the maximum von-Mises equivalent stress.

The results of the fatigue analysis show that the fixing bolt may be damaged by fatigue if MEWP is performed repeatedly for a long time. Therefore, we propose a method to prevent the failure of the fixing bolt of the MEWP from four different standpoints— the manufacturer, safety certification authority, safety inspection agency, and owner. The manufacturer should design not only a structural analysis but also a fatigue analysis, and the safety certification authority should check the results of the fatigue analysis. In addition, the safety inspection agency should inspect the crack through non-destructive means, and the owners should replace the cracked fixing bolts and replace the entire fixing bolt set at regular intervals (e.g., 5 or 10 years).

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Table 1. Number of injuries in the last 10 years*

Year	**Total**	**2008**	**2009**	**2010**	**2011**	**2012**
Fatalities	275	24	19	23	24	30
Injuries	60	9	6	4	8	5
Year	**2013**	**2014**	**2015**	**2016**	**2017**	**2018.4.**
Fatalities	29	35	28	29	28	6
Injuries	2	8	7	9	1	1

* Note. Sourced and modified from KOSHA (2018-SAFETY-876). 2018. In-depth Analysis Report of the Accident at the Mobile Elevating Work Platform in the last 10 years. Ch. 3. pp. 38. Adapted with permission.

Table 2. Number of accidents caused by mechanical defects in the last 10 years*

Types of defects	Accidents
Total	42
Wire-rope	13
Boom welding	9
Turntable fixing bolts	9
Work platform support	8
Derrick cylinder	3

* Note. Sourced and modified from KOSHA (2018-SAFETY-876). 2018. In-depth Analysis Report of the Accident at the Mobile Elevating Work Platform in the last 10 years. Ch. 5. pp. 152. Adapted with permission.

Table 3. Chemical composition analysis results of the fractured fixing bolt (mass, %)

Elements	**C**	**Mn**	**P**	**S**
Bolt(R10)	0.20452	0.79529	0.01741	0.00342
Required values (Class 10.9 standard)	0.15~0.35	≥ 0.7	≤ 0.035	≤ 0.035

Table 4. Mechanical properties of the fractured fixing bolt (MPa)

Strength	**Tensile strength**	**Yield strength**
Bolt(R10)	1217	1092
Required values **(Class 10.9 standard)**	≥ 1000	≥ 900

Table 5. The number of nodes and elements of FEM according to boom angle

Boom angle	**nodes**	**elemnets**
0°	70,667	32,890
20°	71,631	33,250
40°	68,404	31,365
60°	70,274	32,348
80°	67,193	31,034

Table 6. The mechanical properties used in structural analysis

Materials	Young's Modulus (GPa)	Poisson's ratio	Density (kg/m^3)	Yield Strength (MPa)	Tensile Strength (MPa)
ATOS80	207	0.29	7850	813	880
SS400	200	0.29	7850	250	460
SM45C	207	0.3	7600	490	686
S45C	205	0.29	7850	1,132	1,245
S48C	200	0.27	7700	365	610
STC60	202	0.27	7800	520	588

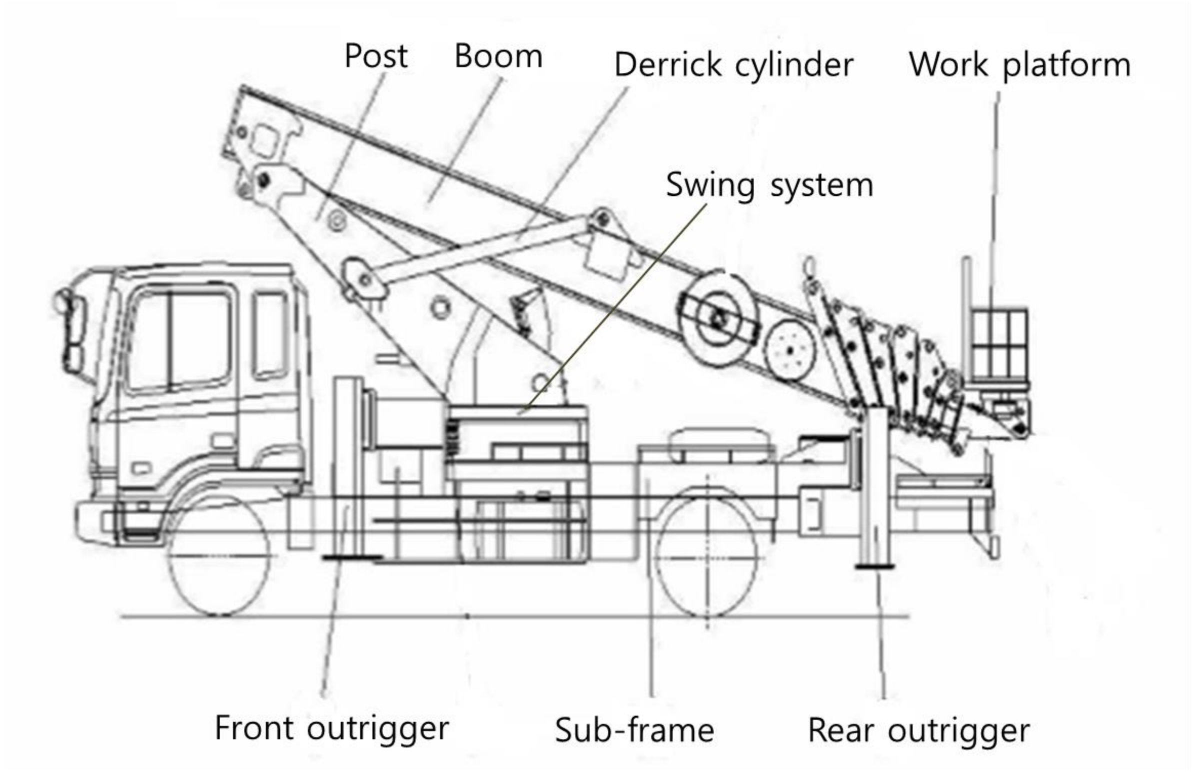

Fig. 1. Schematic of mobile elevating work platform working device*

* Note. Sourced and modified from HANSIN SPECIAL EQUIPMEMT CO. Instruction Manual and Repairing Guide. Adapted with permission.

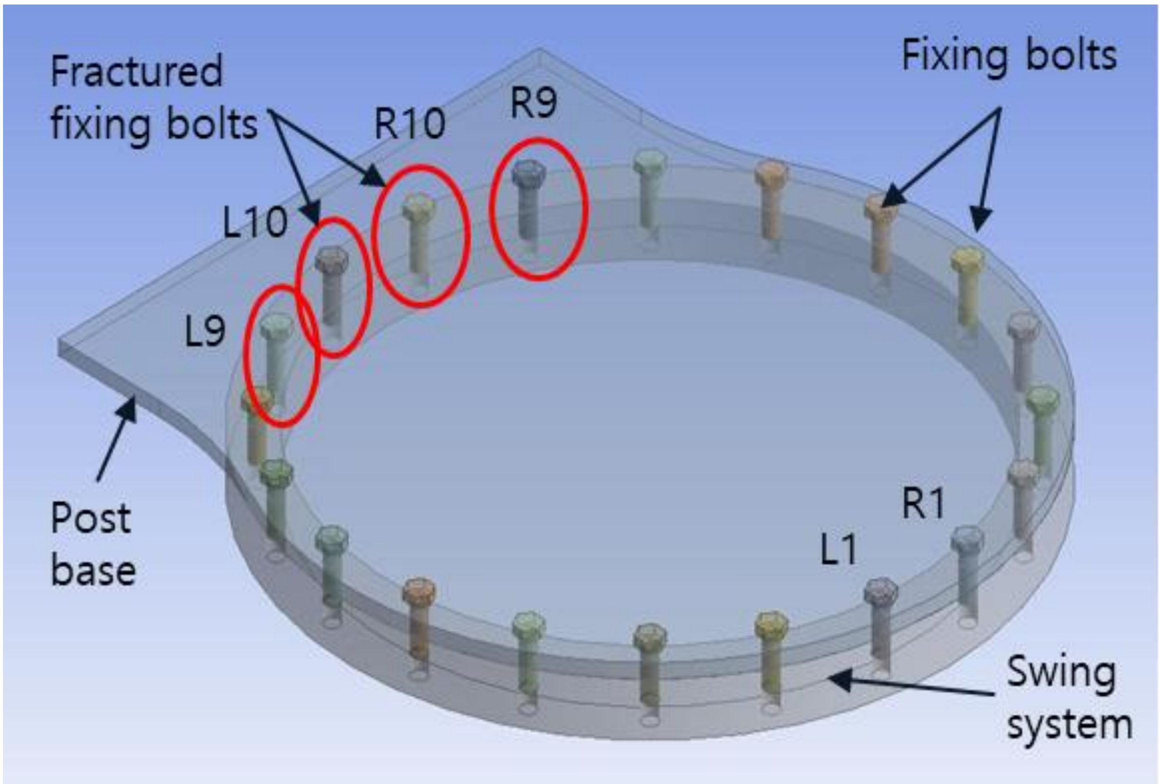

Fig. 2. The set of 20 turntable fixing bolts and 4 fractured bolts

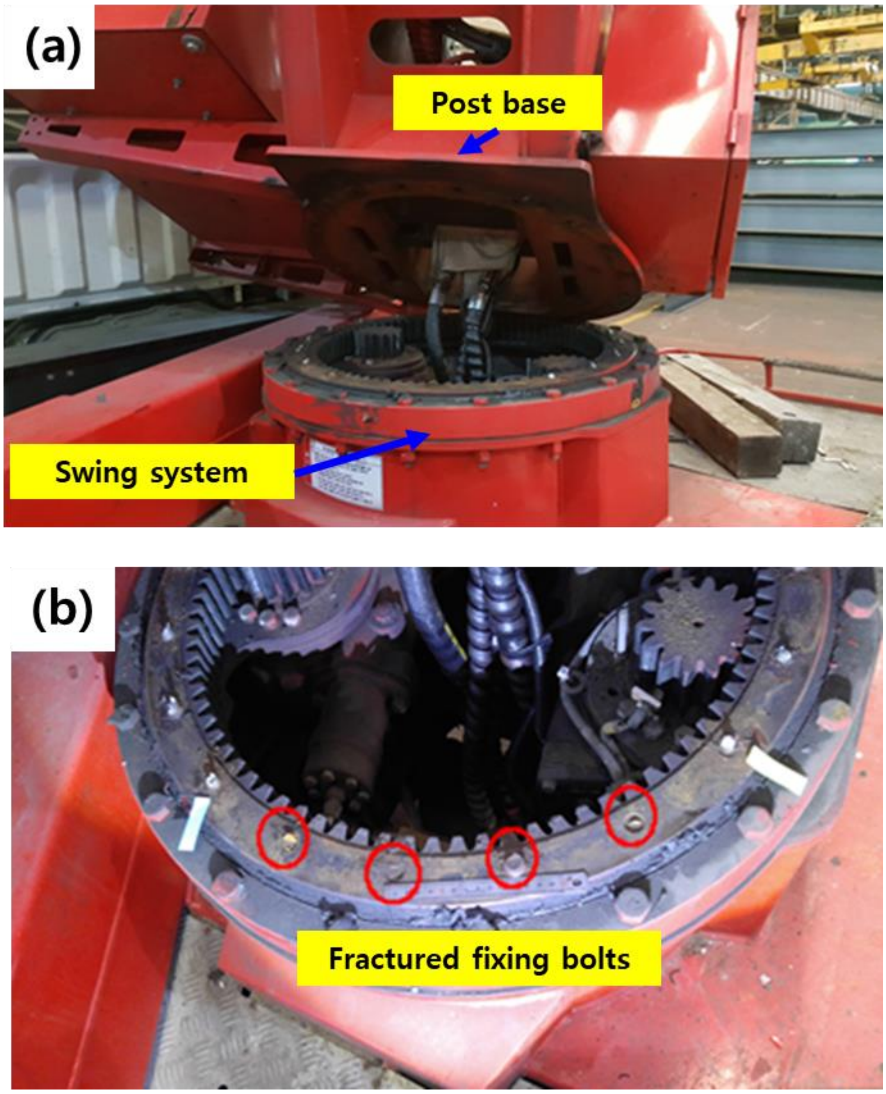

Fig. 3. Failure scene of the fractured turntable fixing bolts: (a) turntable and boom after the accident and (b) fractured fixing bolts

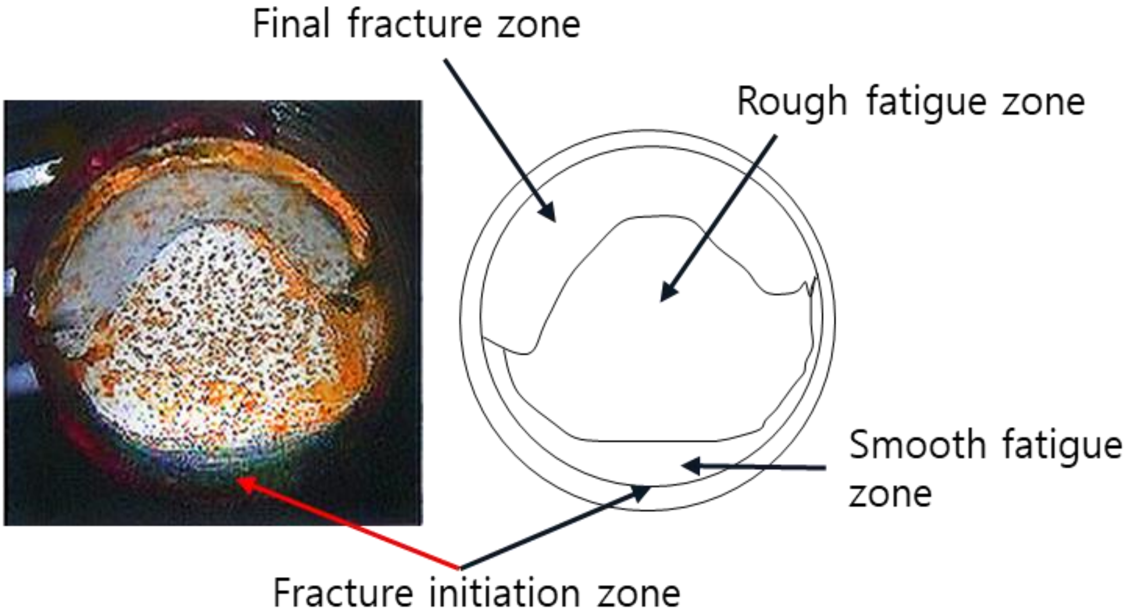

Fig. 4. Macrograph and schematic of fracture surface of one of the fixing bolts (R10)

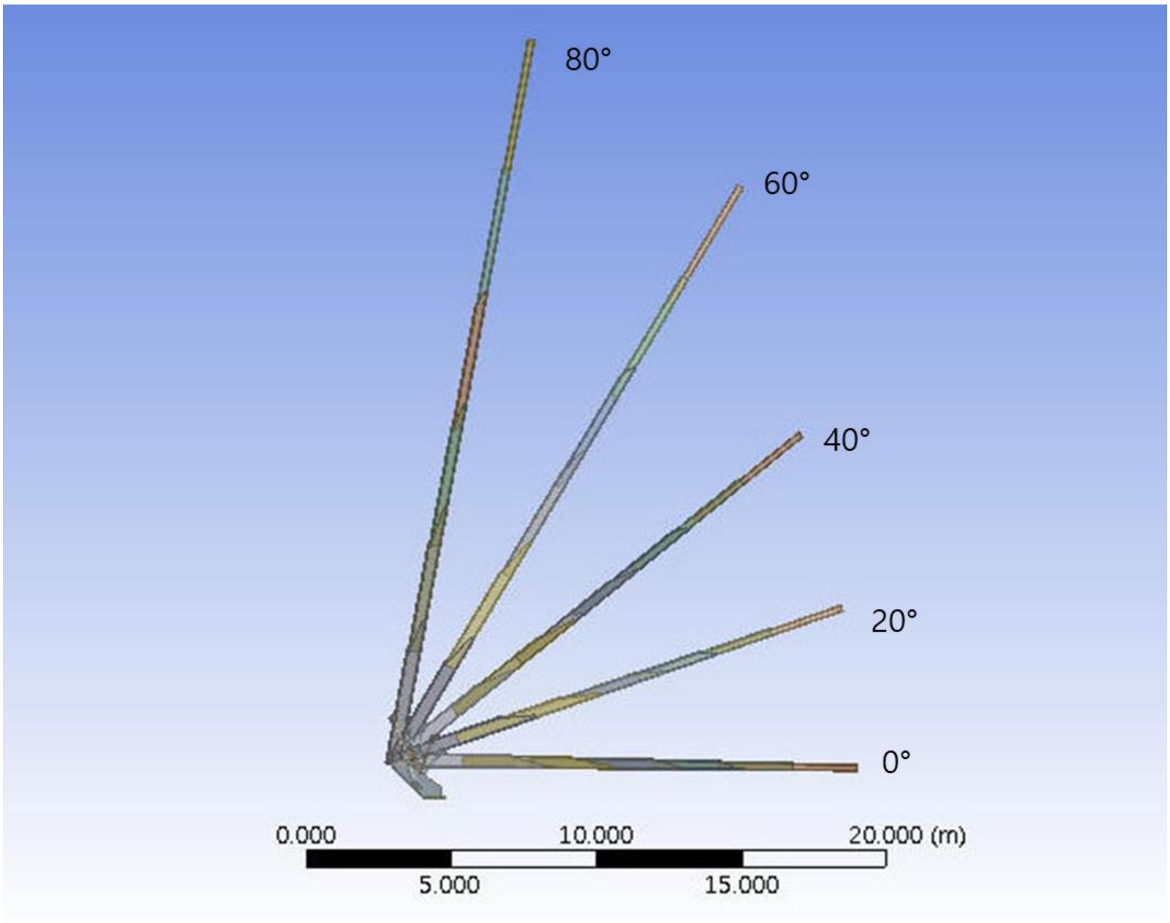

Fig. 5. Geometrical model of the MEWP in working radius

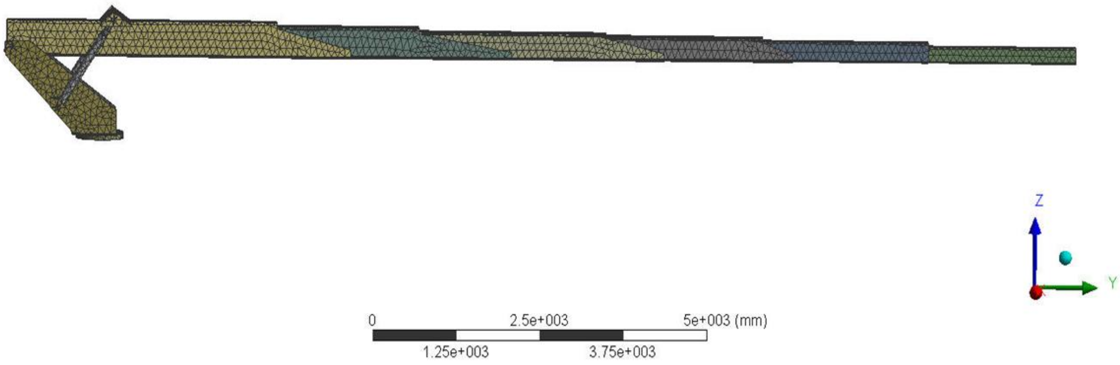

Fig. 6. Finite element model when boom angle is 0°

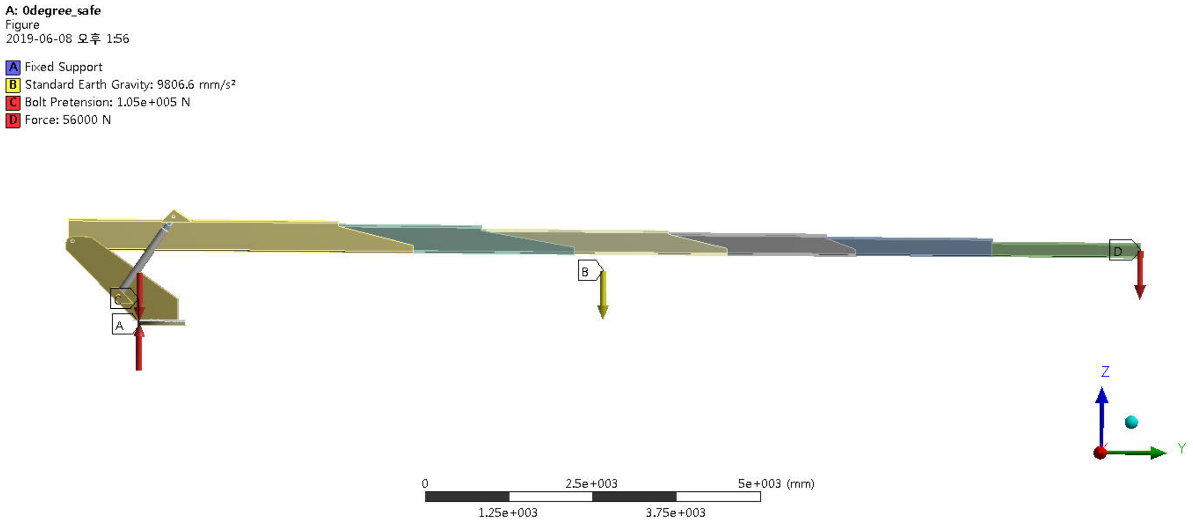

Fig. 7. Boundary condition when boom angle is 0°

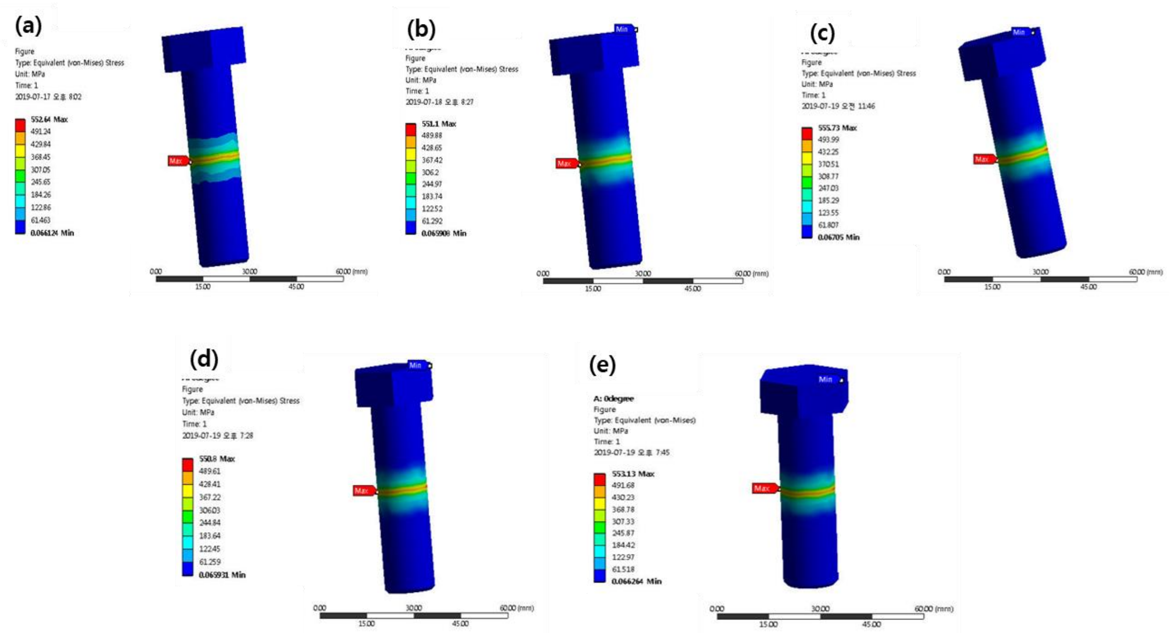

Fig. 8. Von Mises equivalent stress distribution on the fixing bolt according to boom angle from 0° to 80°: (a) 0°, (b) 20°, (c) 40°, (d) 60°, (e) 80°

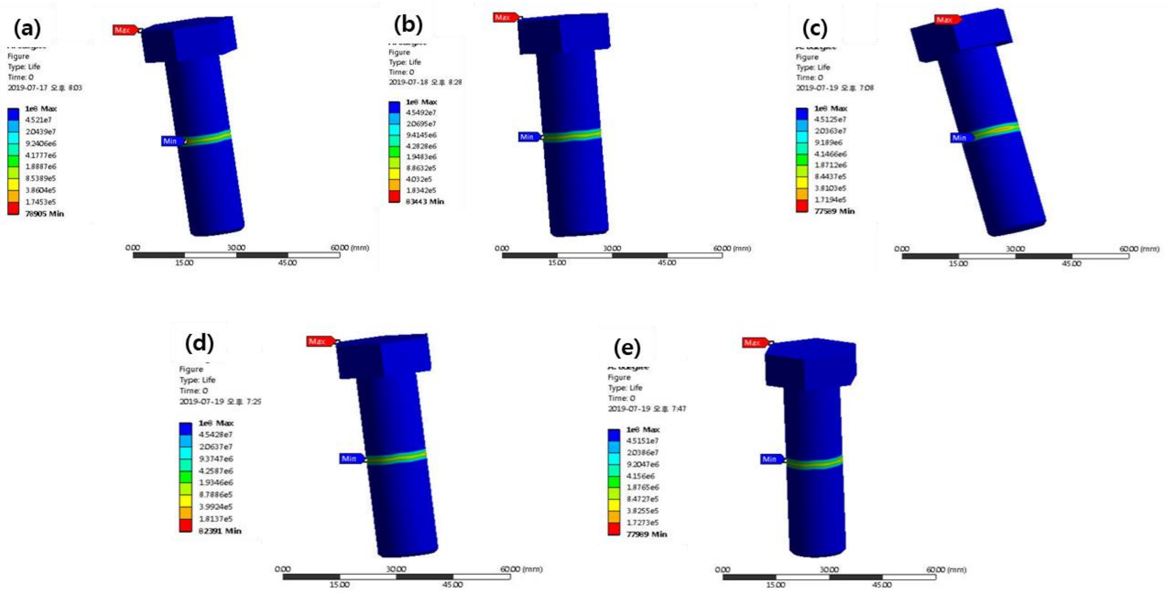

Fig. 9. Fatigue life simulations of the fixing bolt according to boom angle from 0° to 80°: (a) 0°, (b) 20°, (c) 40°, (d) 60°, (e) 80°

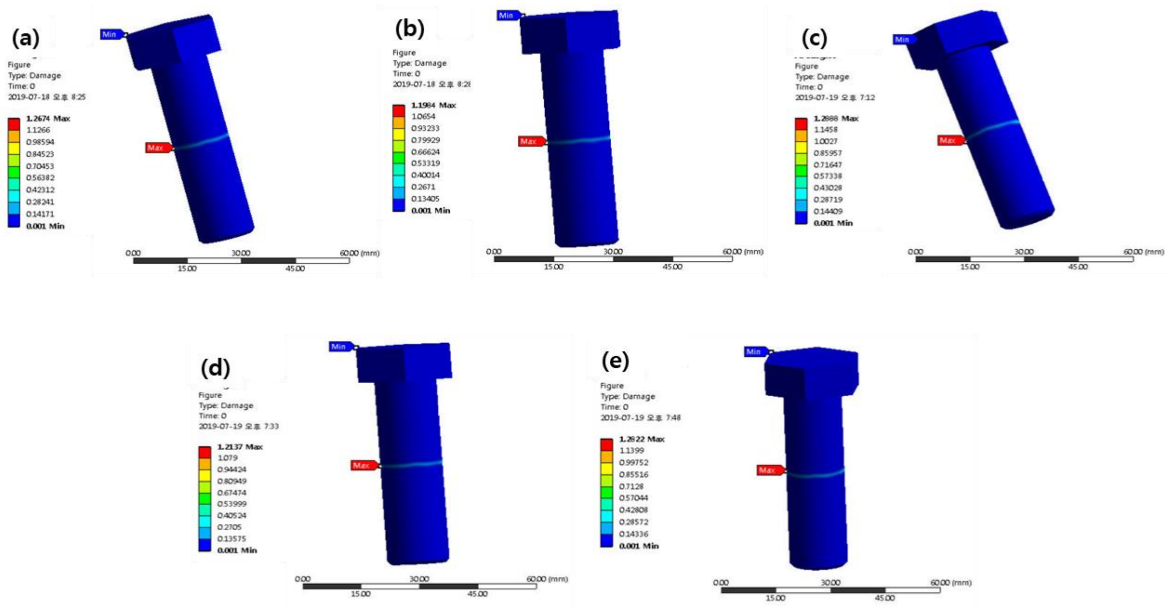

Fig. 10. Fatigue damage contours of the fixing bolt according to boom angle from 0° to 80°: (a) 0°, (b) 20°, (c) 40°, (d) 60°, (e) 80°

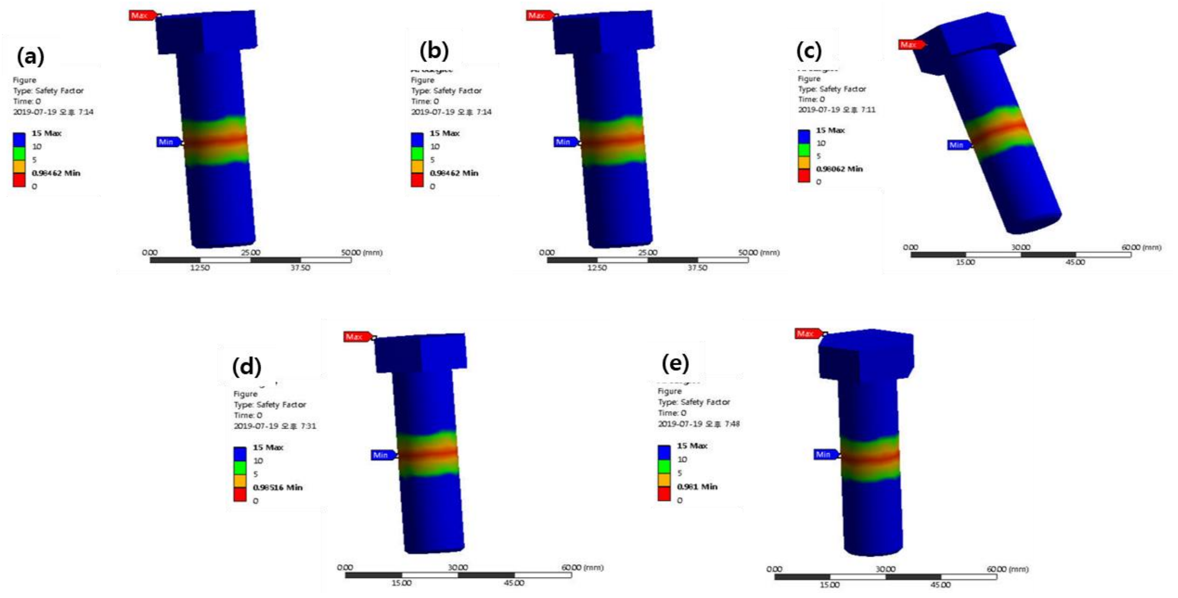

Fig. 11. Minimum safety areas on the fixing bolt according to boom angle from 0° to 80°: (a) 0°, (b) 20°, (c) 40°, (d) 60°, (e) 80°