

70/15 ton×105 m 레벨러핑 크레인의 구조해석

Structural Analysis for a 70/15 ton×105 m Level Luffing Crane

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Evaluation of the structural analysis for a 70/15 ton×105 m LLC (Level Luffing Crane) was conducted with an FEM Tool. Due to a discordance of the modeling and element type, the LLC was progressively analyzed after dividing it into the boom, main structure and rocker. All loads such as slewing, traveling and wind load, etc., that are indicated in the reference standards, were inputted as various severe conditions of the LLC. The deformation, equivalent stress (Von Mises stress), buckling characteristics were evaluated for the LLC structures. The stress concentrated areas over the allowable stress were identified, and reinforcement work was performed with a stiffener.

Key Words: Finite Element method (유한요소법), Level Luffing Crane (레벨러핑 크레인), Equivalent stress (등가응력), Buckling (버클링)

1. Introduction

The Korean shipbuilding industry built over 40% of all ships delivered worldwide in 2007, and the most complex freighters such as the liquefied natural gas (LNG) carrier, huge container vessel, and oil-exploring drill ship are built by Korean companies. The rapid expansion in the shipbuilding industry and a larger trend towards marine structures have led to a growing need for a huge specific crane – the goliath crane, level luffing crane (LLC) - for high productivity and creation of value added.

A big LLC with a rated load of 70 tons and slewing circle of 105 m (70/15 ton×105 m LLC) was made by CTC co. A structural analysis was conducted with an

FEM program in order to evaluate the safety and integrity of the LLC. The 70/15 ton×105 m LLC is a kind of overhead crane and a traveling machine that rides on a runway structure or a pair of tracks above the work floor, and consists of a main body, boom and rocker sections.^{1,2}

Because an LLC should be ensured against buckling, deformation, stress, vibration and fatigue, a procedure and method to evaluate its stability are presented through the related specifications.³⁻⁵ But, this evaluation is limited by the crane's complexity and the various working environments. The FEM analysis with deformation, equivalent stress, buckling and natural frequency, etc. is an increasingly popular choice for evaluating the structures.⁶⁻⁹ Almost all analyses are also substantially restricted due to a modeling method using beam

elements.^{10,11} In this paper, all LLC structures except the boom were modeled with solid element for detail load and stress embodiment.

2. Structure of the 70/15 ton×105 m LLC

The LLC has a boom that is used to project the upper end of the hoisting tackle with a hook in a reach direction or in a combination of height and reach. The boom is composed of over 620 pipes and is connected with an A-shape structure (referred to “A-structure”) to the main body (Fig. 1). The boom could be placed in varied angles (-30°~71°) according to the working requirement since the upper part of the boom links up with the pulley of the A-structure’s top block section with two luff ropes and one main rope, and the lower part of the boom links up with the front two hinge sections of the A-structure’s machinery deck by boom mounts.

The A-structure consists of a front post, backstay and top block that are linked with many kinds of ropes. The boom and machinery deck including the drums, engineer room, weight ballast, etc., are coupled to the A-structure by hinges. And other structures of the LLC such as a tower, a girder, and legs are designed to resist due to rotation of the tower and rockers for traveling. The structure of the LLC is shown as Fig. 1.

3. Analysis Procedures

The LLC was modeled in three dimensions by commercial software (CATIA Ver. 5. and SolidWorks 2006). The boom was modeled with beam elements, and other structures were modeled with solid elements. Therefore, the LLC is classified into three sections, namely the boom, main body and rocker. First, the boom part was analyzed after considering the boundary conditions and received load, which are the self weight of the boom and ropes, the working load in the hook, and the slewing and traveling load, etc. The force and moment values at the four physically connected parts were obtained and then were inputted into the main body to evaluate its safety.

The rocker structure with wheels was judged through the normal reaction force by the main body’s legs. An FEM analysis was carried out with ANSYS Workbench

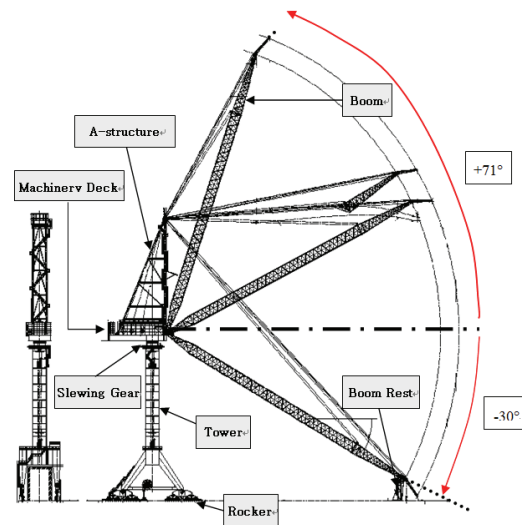


Fig. 1 The 70/15 ton × 105 m LLC structure

Table 1 The 70/105 ton × 150 m LLC conditions

Classification		Cases	Boom analysis	Main structure analysis	Rocker analysis
Long term	1	90-42m × 70 ton-NW	O	O	
	2	90-60m × 60 ton-NW	O		
	3	90-99m × 35 ton-NW	O	O	
	4	90-105m × 25 ton-NW	O		
Mid term	5	90-42 m × 70 ton-W	O	O	
	6	90-60 m × 60 ton-W	O		
	7	90-99 m × 35 ton-W	O	O	
	8	90-105 m × 25 ton-W	O		
Short Term	9	0-Rest × no Load-0W	O	O	
	10	0-Rest × no Load-90W	O	O	O
Others	11	59-99m × 35 ton-NW	O	O	O
	12	59-99m × 35 ton-W	O	O	O
Remark	<p style="text-align: center;">90-42m × 70 ton-NW</p> <p style="text-align: center;">↙ ↘ ↙ ↘ ↙ ↘ ↙ ↘</p> <p style="text-align: center;">slew angle radius hook load wind condition</p>				

* Wind has zero angle when the LLC is in front center and the right hand direction is positive

Table 2 The 70/105 ton × 150 m LLC load conditions

Classification	SW	Load	SW-TL	Load-TL	SW-SL	Load-SL
Long term (no wind)	K	$K \times \psi$	$K \times \beta_{TL}$		$K \times \beta_{SL}$	
Mid term (wind : 20 m/s)	K	$K \times \psi$	$K \times \beta_{TL}$		$K \times \beta_{SL}$	
Short term (wind : 56 m/s)	1	-	-	-	-	-
Rocker	1		0.05		-	
Remark	*abbreviation SW: Self Weight, TL: Traveling, SL: Slewing *K(duty factor) : 1.08 , ψ (impact factor) : 1.1 , β_{TL} : 0.044, β_{SL} : 0.018~0.071					

Table 3 Material properties

Longitudinal modulus of elasticity, E	206,000 N/mm ²
Poisson's ratio, ν	0.3
Density, ρ	7.85 g/cm ³

Ver. 10 and ANSYS Classic Ver. 9 in order to express the ropes with non-linear properties.

The LLC should be divided into many conditions according to angle between the boom and main body, boom angle (or working radius), hook working load and wind conditions, as shown in Table 1. All LLC conditions were grouped into long-term, medium-term and short-term categories by wind intensity; no wind is considered for long-term category, 20 m/s wind velocity is for medium-term category, and finally 56 m/s wind velocity is for short-term category.

In the long-term and medium-term categories, every load that contains the self weight, working load, slewing and traveling load were considered with a traveling factor (β_{TL}) and slewing factor (β_{SL}) related to the inertial force, duty factor (K) and impact factor (ψ). In the short-term category, all factors were disregarded due to the boom's rest position and no present load conditions. The β_{TL} was acquired at a speed of 30 m/min and the β_{SL} was obtained during 0.2 rpm based on the reference specification, JIS B 8831. The rocker analysis used a load condition where the load was the maximum value obtained in the bottom of the leg's sections. The same load was applied in the perpendicular direction and 0.05 times load was applied in the horizontal direction. The load conditions of the LLC are indicated in Table. 2.

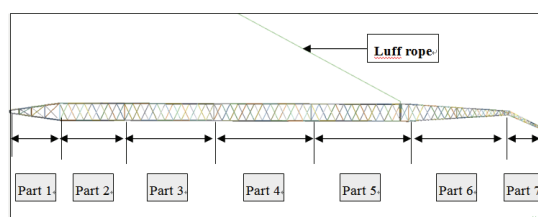


Fig. 2 Boom partition



Fig. 3 Boom meshing result

Table 3 shows the longitudinal modulus of elasticity, Poisson's ratio and density values that are the general properties in the steel.

4. FEM analysis and results

4.1 Boom

4.1.1 Boom modeling

Five types of booms (71°, 61°, 33°, 27°, -30°) were modeled because the boom angles change with the variation of the working radius or hook loads. The boom is divided into 7 parts for convenience to promote the benefit of positioning, as shown in Fig. 2. There are 4,200 total nodes and 4,600 elements after meshing and the resultant mesh is shown in Fig. 3. The left/right (L/R) luff rope and L/R boom mount were fixed to acquire reaction forces and moments at the linked point with the main body.

4.1.2 Luff ropes modeling

Wire ropes are classified by the number of strands and the nominal number of wires in the strand, such as 6×19 or 6×25. Ropes are also grouped by the strand's

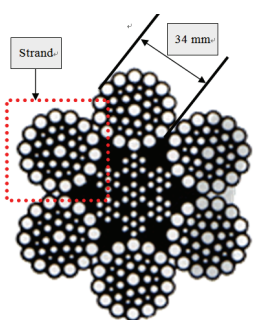


Fig. 4 Wire rope constructions (6x36 IWRC)

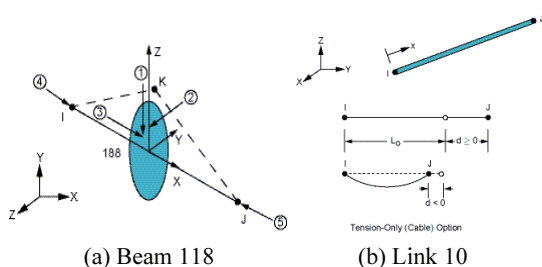


Fig. 5 Luff rope element type comparisons: (a) 3-D linear finite strain beam, (b) tension-only spar

array condition. The rope type in the luff ropes is a 6x36 IWRC (independent wire-rope core); the core works to support the strands by keeping them in position, and the wire cores add strength to the rope. Fig. 4 shows the construction of the wire rope used. A cable material (luff rope) having a non-linear property could not be adequately expressed since element types are restricted in the ANSYS WorkBench. In order to analyze the boom's luff rope, the 'beam 188' elements were changed into 'link 10' elements that could deliver a tension force without strain. Fig. 5 shows each element type.¹²

4.1.3 FEM results of the boom part

Reaction forces and moments in the LLC boom's fixed points were acquired in order to analyze the main body. Table 4 shows values at an angle of 70° both when wind is and is not present. The right luff rope is compressed due to the boom's slewing, the main body's traveling and the wind pressure in this case.

For these reasons, the Z-axis (slewing direction) reaction force is zero and the Y-axis (gravity direction) reaction force is 7767 N, which is equal to the luff rope's self weight in the fixed point of the right luff rope. The

Table 4 Reaction force and moment of the boom (in 70° angle)

Case	Fix points	90-42 m × 70 ton-NW	90-42 m × 70 ton-W	
Force (kN)	Luff rope L/H	x	5.7	5.7
		y	-322.6	-322.6
		z	-221.6	-221.6
	Luff rope R/H	x	0.3	0.3
		y	7.8	7.8
		z	0	0
	Boom Mount L/H	x	26.1	66.8
		y	386.1	-348.4
		z	65.4	-188.3
	Boom Mount R/H	x	108.4	149.2
		y	3362.5	4097.1
		z	1072.3	1326.1
Total	x	140.6	222.1	
	y	3433.7	3433.8	
	z	916.1	916.1	
Moment (kN×m)	Boom Mount L/H	x	0.0	0.0
		y	2.18	5.64
		z	-19.27	-28.44
	Boom Mount R/H	x	0.00	0.00
		y	3.88	7.38
		z	-15.17	-24.33
	Total	x	0.00	0.00
		y	6.07	13.02
		z	-34.44	-52.77

X-axis moment values of the L/R boom mounts were zero in all conditions because those mounts are connected to the machinery decks by a hinge bearing. The X, Y, Z directional deformation values were obtained using the ANSYS Classic program in the major 7 check points (C.P.), which are the end beams of the 7 parts mentioned in Fig. 2. The X-directional maximum deformation is -761.68 mm in the 7th C.P. of the 90-42 m×70 ton-W case. The Y-directional deformation values were over 150 mm in the 3rd C.P. for almost all cases. Finally, the Z-directional maximum deformation value is 762.11 mm in the 7th C.P. of the 90-42 m×70 ton-W case.

The cables of the left and right luff rope would have tensile stress in the longitudinal direction. But the R/H luff rope of 4 cases including the 90-42 m×70 ton-W case has no tension (0 N) because all cables have cable elements delivering only a tensile force. The maximum tension value is about 1206.7 kN in the R/H luff rope of the 90-99 m×35 ton -W, as is shown in Table 5.

Table 5 Cable tension of the boom luff

Cases		Luff Rope tension (kN)
90-42 m × 70 ton - NW	L/H	398.0
	R/H	0.0
90-42 m × 70 ton - W	L/H	425.9
	R/H	0.0
90-60 m × 60 ton - NW	L/H	624.9
	R/H	0.0
90-60 m × 60 ton - W	L/H	624.9
	R/H	0.0
90-99 m × 35 ton - NW	L/H	208.7
	R/H	989.7
90-99 m × 35 ton - W	L/H	0.0
	R/H	1206.2
90-105 m × 25 ton - NW	L/H	332.7
	R/H	941.4
90-105 m × 25 ton - W	L/H	182.6
	R/H	1091.5
0-rest × no Load-0°Wind	L/H	775.4
	R/H	887.0
0-rest × no Load-90°Wind	L/H	974.4
	R/H	729.1
58.67-99 m × 35 ton - NW	L/H	234.6
	R/H	934.9
58.67-99 m × 35 ton - W	L/H	201.3

Table 6 Allowable stress of the boom's each step

Long term		Mid term		Short term	
tension (MPa)	compression (MPa)	tension (MPa)	compression (MPa)	tension (MPa)	compression (MPa)
260	226	299	260	338	293

In the boom modeled with the beam element, the equivalent stress (Von Mises stress), which is a scalar function for the purposes of the calculation yield criteria, was obtained to evaluate the boom's stress conditions. The major vulnerable parts (Fig. 6) were checked in the long, medium and short term conditions. The resultant maximum equivalent stress value is about 165 MPa, which is no more than the allowable stress mentioned in Table 6.

Buckling is an important factor in the crane's intensity evaluation since it is a failure mode characterized by a sudden failure of a structural member subjected to high compressive stresses such as boom pipes. Microscopic buckling occurred in the 1st buckling mode, while operating a load 5.37 times as large as the given load in the 90-99 m×35 ton-W case in Fig. 7. The

Table 7 Natural frequency and natural mode of the boom

Angle	unit : Hz					
	1st X-bending mode	1st Y-torsion mode	2nd X-bending mode	1st Z-bending mode	2nd Y-torsion mode	3rd X-bending mode
71°	0.52	0.69	0.83	1.20	1.89	1.97
61°	0.52	0.88	0.96	1.26	1.94	2.00
33°	0.51	0.94	0.96	1.29	1.44	1.46
27°	0.51	0.95	0.97	1.28	1.32	1.35
-30°	0.51	0.96	0.98	1.29	1.41	1.43

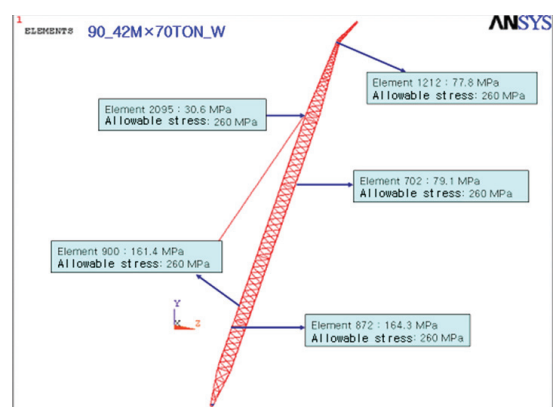


Fig. 6 Equivalent stress of the boom in 90-42 m×70 ton-W

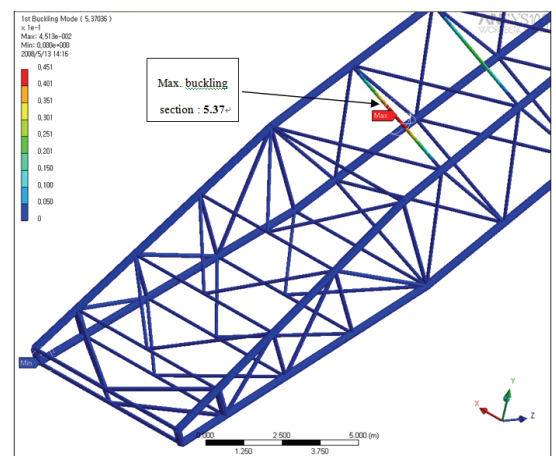


Fig. 7 Buckling result of the boom in 90-99 m×35 ton-W

boom of the crane was determined to have a superior buckling safety since other cases also bear a curious likeness to the 90-99 m×35 ton-W case.

When wind, earthquake and a crane motor's vibration would be harmonized with the natural frequency of the boom, the resonance phenomenon would cause the structural failure. The 6 kinds of low frequencies were calculated for the 71°, 61°, 33°, 27°, -30° boom angles and the results were summarized in Table 7.

These frequencies are unrelated to the vibration field of the crane motor. However, the boom structure could be affected when the wind vibration of equal frequency is applied in the relevant direction, because each frequency of the 1st X-bending mode, the 1st Y-torsion mode and the 1st Z-bending mode is 0.51~0.52 Hz, 0.69~0.96 Hz and 1.20~1.29 Hz, respectively.

4.2 Main structure

4.2.1 Main structure modeling, meshing and the boundary condition

For the evaluation of the LLC main structure, 12 major cases of long, mid and short terms were selected, as mentioned in Table 1. The main structure is made up of the A-structure, machinery deck, tower and leg. The modeling element of the main structure is a solid type and is different from the beam type element used in the boom. The boom was analyzed first due to the dissimilarity in element types, and the reaction forces and moment were obtained in the fixed points; L/H luff supports and L/H boom mounts.

The main structure's body was converted from solid elements into shell elements to reduce the number of nodes and elements. There are about 100,000 total nodes and 93,800 elements after meshing, as is shown in Table 8. The main structure's boundary condition was given as described in Table 9 and Fig. 8 by considering the surrounding of the rocker on the traveling rail when the main structure travels or slews.

The reaction forces and moments were inputted in the luff rope supports and boom mounts in order to analyze the main structure's FEM. Other loads as mentioned in Table 2 such as self weight of the main structure and ropes, load of traveling, slewing and wind, etc., are also applied in the related components according to the crane's conditions and factors.

4.2.2 FEM results of the main structure part

The sum of the reaction forces acquired from the 4

Table 8 Meshing size in the main structure's major sections

section	Meshing size (mm)	section	Meshing size (mm)
Top Block	50	Machinery Deck	200
A-Structure	100	others	300

Table 9 Boundary conditions of the main structure

location	FX	FY	FZ	MX, MY, MZ
Rear_left rocker	fix	fix	free	free
Rear_right rocker	fix	fix	fix	free
Front_left rocker	free	fix	free	free
Front_right rocker	free	fix	fix	free

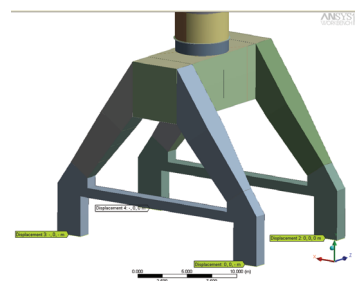


Fig. 8 Main structure boundary condition

Table 10 Reaction force of the main structure (in 70°)

Fix point		90-42 m × 70 ton - NW (kN)	90-42 m × 70 ton - W (kN)
Rear_left rocker	x	405.8	518.7
	y	4914.2	5044.4
	z	0.0	0.0
Rear_right rocker	x	451.8	570.5
	y	5022.9	5157.2
	z	-18.4	-20.8
Front_left rocker	x	0.0	0.0
	y	4102.2	3978.6
	z	0.0	0.0
Rear_right rocker	x	0.0	0.0
	y	4156.3	4015.5
	z	18.3	20.7
Total	x	857.5	1089.2
	y	18195.6	18195.6

fix points of the main structure was equal to the sum of the total self weight and inputted load. The result of the 90-42 m×70 ton case among the 8 evaluated cases is shown in Table 10.

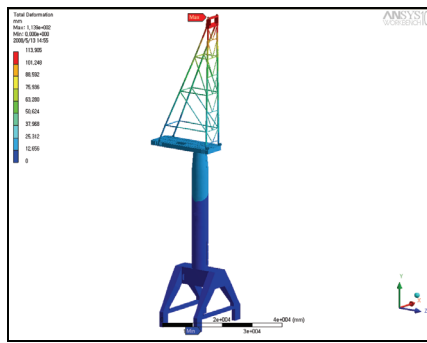


Fig. 9 90-99 m×35 ton-W total deformation

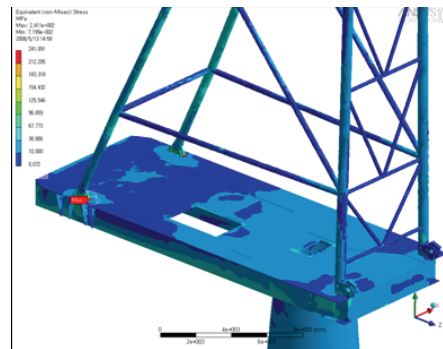
Table 11 Allowable stress of the main structure’s material for each condition

Condition	term	Allowable stress (MPa)	Remark
90-42 m × 70 ton-NW	Long	236 (=355/1.5)	SM490YB’s Yield stress : 355 MPa
90-42 m × 70 ton-W	Mid	272 [= (355/1.5) × 1.15]	
90-99 m × 35 ton-NW	Long	236 (=355/1.5)	
90-99 m × 35 ton-W	Mid	272 [= (355/1.5) × 1.15]	
0-rest × no load-0° Wind	Short	307 [= (355/1.5) × 1.3]	
0-rest × no load-90° Wind	Short	307 [= (355/1.5) × 1.3]	

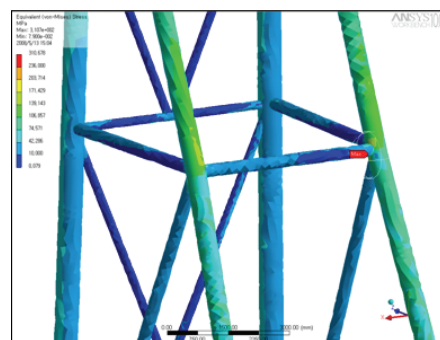
The major section’s X, Y, Z and the total deformations were measured for each condition. The deformation was very small for all cases compared with the LLC structure’s huge size. In the 90-99 m×35 ton-W/NW case, the maximum deformation is 101 mm in the Z-axis and 113 mm in total, as is shown in Fig. 9.

The equivalent stress was obtained to evaluate the main structure’s safety in all 6 cases except for the 58.67-99 m×35 ton-NW/W cases. The main structure used ‘SM 490YB’ as its material, which is a kind of rolled steel with a yield stress of 355 MPa. As a result of this analysis, the acquired maximum equivalent stresses in almost all cases are less than material’s allowable stress, as is shown in Table 11.

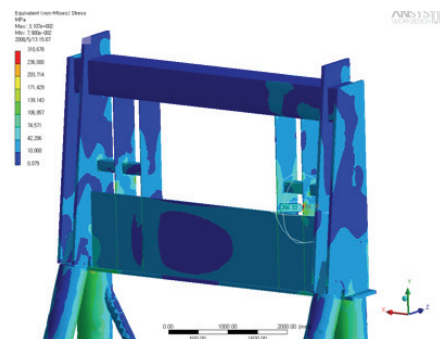
The stress concentration areas are the machinery deck hinge, backstay main pipe and top block’s vertical plates, as shown in Fig. 10. However, the overall structural safety could be ensured because the concentrative stress



(a) Equivalent stress in the 90-42 m×70 ton-NW (Max. 241 MPa): Hinge



(b) Equivalent stress in the 90-99 m×35 ton-NW (Max. 310 MPa): Backstay Pipe



(c) Equivalent stress in the 90-99 m×35 ton-NW (266 MPa): Top block plate

Fig. 10 Major stress concentration area

is not large and these parts are reinforced by both a stiffener and supporter.

Linear buckling analysis also was carried out in the main structure to evaluate the structural safety in a similar manner as the boom. The buckling result in the 90-42 m×70 ton-W case is shown in Fig. 11, which is the

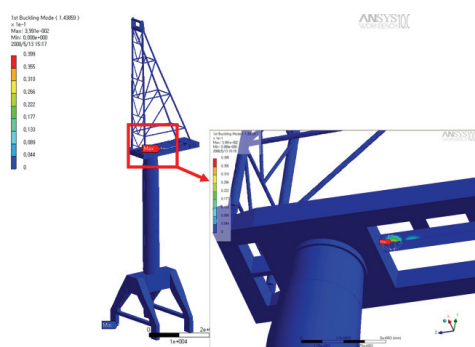


Fig. 11 90-42 m×70 ton-W buckling result

most severe load condition. The main structure was determined to have a superior buckling safety since microscopic buckling occurred in the 1st buckling mode while operating at a load 1.438 times the given load.

5. Conclusions

The huge level luffing crane (LLC) with a rated load of 70 tons and working radius of 105 m was modeled and analyzed with an FEM program in order to evaluate its design safety. The analysis progressed in order of precedence from the boom to rocker since different element types were involved in the analysis. The conclusion provided above can be briefly stated as follows.

(1) The boom was modeled with beam elements and analyzed for 12 cases. We have looked at the cable tension, equivalent stress and buckling of the boom.

(2) The main structure was modeled with shell elements and was analyzed for 8 cases. A stress concentration over the allowable stress was unfortunately observed in the A-structure and machinery deck hinge. However, we conclude that the main structure is sufficiently safe because the concentrative stress is not large and these parts are reinforced by a stiffener. The buckling of the main structure were also found to be superior in the analysis.

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