Research Article

New Generation Ingot Crane Design, Finite Element Analysis (FEA) and Prototype Manufacturing

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Abstract

Within the scope of R&D project, this study encompasses the design, analysis and prototype production of a new generation ingot crane, which is intended for use in the casting and rolling mill parts, especially in the iron and steel industry. The ingot process crane, whose design is conducted within the BVS R&D Center, is a special process crane that incorporates specific equipment tailored to the needs of the customer organization. The ingot crane performs the entire operational process of pouring the molten metal into specific block molds tailored to the desired part geometry, moving the mold to the desired position as per the process requirements, removing (stripping) the mold after the ideal cooling period, and lifting and transporting the resulting block castings and semi-finished products. Considering the process steps of process-based production processes, manpower is limited only to the activities of an operator at the control panel.

In the scope of the R&D project, maximum stress and deflection values have been determined within the framework of boundary conditions, using both analytical and Finite Element Analysis Methods (FEA) at the specified load situations of the ingot process crane carrier beam group. In addition, Von Mises stress conditions have been investigated for the critical regions of the carrier triple beam group, which is a pioneering innovation in the crane industry. As a result of the analysis, no adverse situation was observed in terms of design conditions when both deflection and critical stress situations were taken into account. In this regard, the design of a new generation ingot crane and prototype manufacturing will not only reduce import substitutions, but also contribute to take the companies in the casting field in our country benefit at a more competitive level in terms of both labor and safety in the operational production process.

Keywords: Rolling Mill, Ingot Crane, Process Crane, Finite Element Analysis

1.   Introduction

On a global scale, process cranes that can specifically address the processes of customer organizations in the crane industry are defined as gantry cranes in the heavy-duty class, manufactured according to international standards in response to the demands of organizations in sectors such as the iron and steel industry, primarily represented as the heavy industry sector on international platforms, including rolling mills (casting process), and other sectors with specific product manufacturing processes such as ship machinery. In process cranes, the primary goal is to provide solutions to customer organizations while minimizing labor and time losses by achieve optimal production that is fully compliant with standards and regulations. In addition, the costs of high safety-equipped production processes are minimized due to the production of specialized solutions for particular manufacturing processes.

Figure 1. 335/80 Ton Rolling Mill Casting Crane (MMK Metalurgy and Ports)

Ingot cranes play a crucial role in fulfilling production processes under especially challenging circumstances, such as the operational process of pouring, lifting, and transporting molten metal alloy from a mold to specified degrees. Designing ingot crane with high standards is of great importance for heavy-duty working conditions in these specific production processes. As depicted in Figure 1, a special process crane, that designed by the BVS Cranes R&D Center project team and specifically produced for the heavy-duty iron and steel sector, continues to provide services at the customer organization (İskenderun Demir Çelik A.Ş./İSDEMİR)

Gantry cranes, in essence, are machines where two main supporting girders are connected to two running groups, performing the activities of lifting and transporting loads on rails connected to columns already present in the structural construction. Process cranes, however, can be defined as cranes within the class of gantry cranes designed for specific tasks under heavy working conditions, which are designed to handle high tonnage and functioning with additional equipment and fixture attachments. Currently, gantry cranes with a maximum lifting capacity of 600,000 kg can be manufactured. On the other hand, the main carrier bridge girder lengths offer a wide range of solutions, ranging from 5 to 60 meters in span.

Process cranes are not only used in heavy working conditions in the industry but also integrated as a crucial component into production lines within manufacturing facilities. Moreover, they can be used in different sectors for various production process steps, such as hold-lift-rotate-release, with different design additional equipment that operate in connection with the lifting hook. The lifting equipment used in process cranes can be classified as traverses, buckets, magnets, tongs, clamps, and other specific lifting attachments. These pieces of equipment are custom-designed based on specific tasks to cater to the heavy-duty class [1, 6]. Additionally, in production areas where the ambient temperature factor is high, electrical rooms and operator cabins cooled with industrial type air conditioners are functionally integrated into the crane system structure.

As a result of literature review, numerous academic studies and publications have been conducted specifically on gantry cranes. From these studies, using finite element analysis (FEA) beams with different eccentricity (torsional effect) and span conditions have been compared in terms of collapse (deflection) and stress. The study has identified that, under eccentric loading, stress and collapse values in a lattice-type beam structure significantly decrease [2]. When other studies in the literature are considered, the stress and deflection values of overhead cranes under loading have been compared both by FEA and the analytical methods. It has been stated through real testing and verification processes that the accuracy rates of the results obtained from the finite element model in the simulation environment are quite effective. In addition, it has been determined as a result of finite element analysis that linear FEA is a very suitable, fast and practical solution method for component-based damage analyzes of crane systems [3, 4]. In literature, researches comparing finite element analysis results using different types of shell elements were made, and it was observed as a result of the research that the 3D model created with quadratic shell elements gave more accurate analysis results than other shell elements [5]. Based on literature research at both national and international levels, this study comprises the design and analysis of the ingot process crane, which is the first in the world because the crane system has a three-girder carrier system. Furthermore, analytical calculations, design (modeling), and analysis (FEA) of an ingot process crane with an appropriate capacity have been comprehensively addressed, by taking into account high

tonnage of parts, especially in rolling mills, steel plants, and iron and steel products, as well as the challenges of transporting specific products, considering factors such as the temperature of the product, the variability of the product's physical geometry, and other difficulties in the production lines where the product will be transported.

Considering the design criteria; the deflection values in the beams have been examined through both analytical calculations and the finite element method (FEA), and design criteria have been compared to determine compliance with FEM and ISO standards. In addition, the critical area stress states in the beam and carrier trolley have been examined through static analyzes performed under different loading conditions. Damage formations in the construction structure have been evaluated based on various loading scenarios.

2.   Materials and Methods

2.1. New Generation Ingot Crane Design Parameters and Boundary Conditions

The process of determining the design parameters for the next-generation ingot process crane, designed as a three-carrier bridge beam and possessing the unique quality of being a first in the literature for the three-carrier beam system, planned to operate in the casting sector and having the characteristics of the customer organization's process, have been collectively configured through a research and development project based on orders. This collaborative effort involved the engineering team and the BVS Research and Development Center project team, aligning with specific requirements within the scope of the R&D project. The design of the ingot crane has determined the design boundary conditions for the 1st auxiliary trolley with an 11m lifting height, the 2nd main process trolley with a 6m lifting height, and the 1st Trolley with a lifting capacity of 75 tons (Working Class: 2m)/45 tons (Working Class: 4m) and The 2nd Trolley is designed with a lifting capacity of 35 tons (Working Class: 4m). The carrier beams will be composed of three beams with a span of 20 m (span distance), and it is technically planned for the crane system to operate in a compact coupled structure.

This study provides the opportunity to carry out the process steps of the ingot process, which include pouring molten metal into the mold set, transporting the mold, mold, removing the ingot semi-finished product from the mold and stacking the semi-finished product whose cooling process has been completed, through a single operational process using the new generation ingot crane with the assistance of an operator. In this context, considering unit cost, production time, and occupational safety, the production process will be effectively addressed through the design of an efficient crane set, providing an operational solution. Additionally, in terms of effective maintenance operations, design features that provide ease of maintenance and labor savings with automatic lubrication systems for long-term usage are directly integrated into the ingot crane structure. On the

other hand, ingot crane have been designed to provide the ability to work under heavy class working conditions at a maximum field ambient temperature of 65°C and the ability to work for more than 16 hours per day.
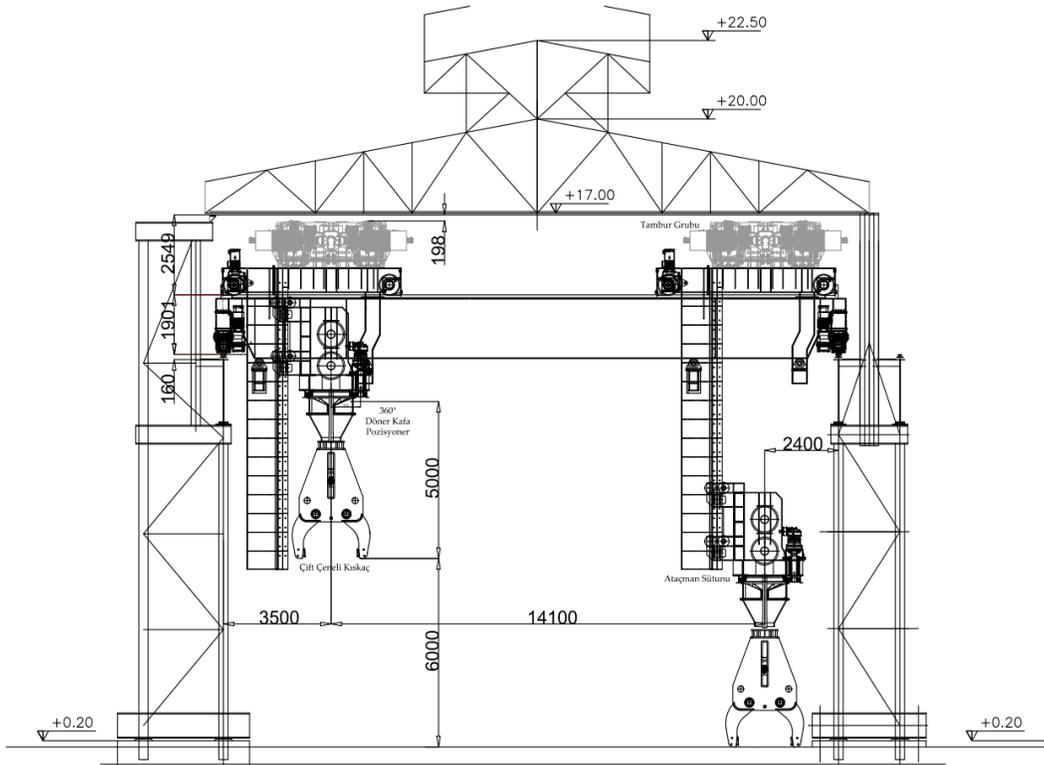

Figure 2. New Generation Ingot Crane Design 2D Sketch Pose View

As a solution to the operational ingot crane production process, a design setup with three beams and two trolleys has been planned. Positioned in the middle, the carrier beam will play a direct role in the movement and transportation of the double-jaw gripper, which has the ability to rotate 360°. On the other hand, it allows direct use during the lifting and positioning of ingot molds during the process. The rudimentary technical drawing detail of the ingot crane to be used for the casting industry in the project development process is shown in Figure 2.

The up-down movement of the 360° rotating gripper attachment will be provided directly by the rope-drum-motor/reducer group [9]. The up-and-down movement in the gripper construction is determined to be carried out more stably, rigidly, and precisely by using the slides on the column with the help of the bearing guide wheels on the chassis. The main beam in the middle is designed to balance both the load from the two separate car groups and the load from the column gripper. Moreover, to prevent unwanted inertias due to sudden accelerations, the rapid rotation of the gripper attachment during

operation will not be allowed for sudden accelerations. Optimal rotation speeds for the design have been specified through speed control drive systems.
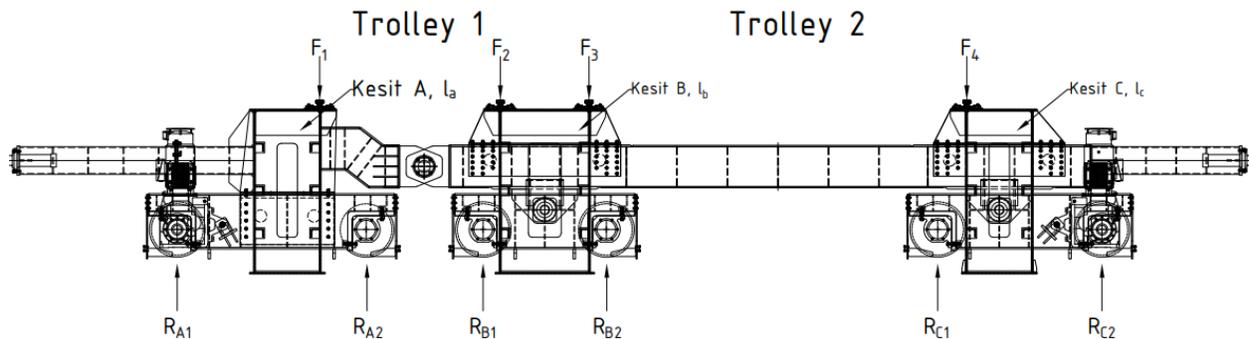

Figure 3. Force and Wheel Reactions Exposed to the Carrier Bridge Beam and Bogie Section

The forces acting on the cross-sections of the bridge beams, which are the main carriers in the ingot crane design, and the reaction forces occurring on the wheels where the execution process is carried out are given in Figure 3. The connection between sections A-B is made through a joint that provides freedom of rotation. The carrier beams will be driven by a total of four motors, two on one side, to provide movement. Considering the operating conditions of the cars in a loaded state, the deflection (collapse) values have been taken into account parametrically both between Section A and Section B, as well as between Section B and Section C.

In the situation in which the column-mounted rotating crane carriage (Trolley 2) is at maximum load, while the other auxiliary car is in an unloaded state (unbalanced), has been identified as the most critical condition for the occurrence of critical transport and movement. Finite element analysis (FEA) has been conducted with precision to ensure minimal deflection (collapse) in order for the carrier car groups to operate effectively and safely. With the BVS Cranes R&D Center project development experience and preliminary design analytical calculations, it was determined that the parametric level difference (deflection) in the carrier beam design criterion should be a **maximum of 20 mm**, according to FEM and ISO standards. The inertias of beam sections in the load-carrying condition are defined as Ia, Ib, and Ic. The relationship between inertias has been defined as Ib = kxIa = kxIc for the specified design constraint. Current design parameters and boundary conditions have led to the determination of a beam section that is more rigid compared to a standard existing beam with the same span and load-carrying capacity.

2.2 Studies in Modeling and Analysis of Ingot Crane (FEA)

2.2.1 Analytical Calculations for Crane System Carrier Box Beam Deflection (Collapse)

The load carried by the beams, along with the trolley and hook assembly, attachments, and equipment are schematically placed between the carrier beams as seen in Figure 3, as they will operate in two loading conditions: 1st trolley and 2nd trolley loading situation. To obtain deflection values for the beams designed specifically for the customer organization's process project, the deflection equations were configured as follows;

Q_G: Self Weight of the Crane Beam Set,

Q_T: The Weight of the Trolley, Hook, and Rope,

Q_L; Defined as the Maximum Load the Beam Can Carry.

Deflection equations [4-5] are given according to the maximum reaction forces on the wheel. The forces F1, F2, F3 and F4 are obtained from the equations given below. The loads for two different trolley loads are defined as $Q_G(1)$, $Q_T(1)$, $Q_L(1)$ and $Q_G(2)$, $Q_T(2)$, $Q_L(2)$.

In the loaded state, F1 force represents the forces acting on section A, F2 and F3 forces represent section B, and F4 force represents section C of the beam."

$F_1 = (Q_{GA} + Q_T(1)/2 + Q_L(1))/2 = R_{A1} + R_{A2}$

$F_2 = Q_{GB} + Q_T(1)/2 + Q_L(1)/2$

$F_3 = Q_{GB} + Q_T(2)/2 + Q_L(2)/2$

$F_4 = Q_{GC} + Q_T(2)/2 + Q_L(2)/2 = R_{C1} + R_{C2}$

$F_2 + F_3 = R_{B1} + R_{B2}$ [1]

"δ_A" and "δ_B" values given below are the deflection amounts resulting from the effect of the trolleys on the beams in the loaded condition. According to the superposition principle in terminology, the total deflection value is calculated by summing the deflection values coming from each load. Here;

I_x: Moment of Inertia of the Beam Sections on the x-axis,

L: Length of the Beam,

c: Minimum Distance That the Trolley Approach to the Beam Wheel Group (Headline) (c≈1 m),
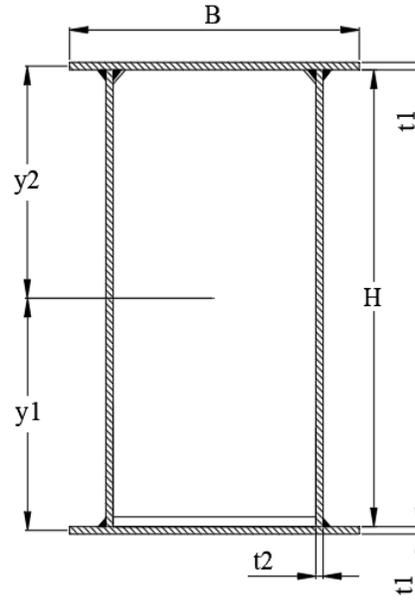
E: Elasticity Module

Figure 4. Ingot Crane Carrier Sheet Artificial Box Beam Section Detail

The beam section detail is given in Figure 4. The moment of inertia I_X for the beam section is calculated using equation (2):

$$I_X = 2 \text{ x } \left(\frac{t_2 H^3}{12} + \frac{B t_1^3}{12} \right) + A_1 \text{ x } (y_1^2 + y_2^2) \tag{2}$$

$$\delta_A = \delta_G + \delta_T + \delta_L \tag{3}$$

$$\delta_B = \delta_G + \delta_T + \delta_L \tag{4}$$

$$\delta_C = \delta_G + \delta_T + \delta_L \tag{5}$$

$$\delta_A = \frac{5*(Q_{GA})*L^4}{384*E*Ixa} + \frac{(R_{A1T}+R_{A2T})*c*(3*L^2-4*c^2)}{24*E*Ixa} + \frac{(R_{A1L}+R_{A2L})*c*(3*L^2-4*c^2)}{24*E*Ixa} \tag{6}$$

$$\delta_B = \frac{5*(Q_{GB})*L^4}{384*E*Ixb} + \frac{(R_{B1T}+R_{B2T})*c*(3*L^2-4*c^2)}{24*E*Ixb} + \frac{(R_{B1L}+R_{B2L})*c*(3*L^2-4*c^2)}{24*E*Ixb}$$

$$\delta_C = \frac{5*(Q_{GC})*L^4}{384*E*Ixc} + \frac{(R_{C1T}+R_{C2T})*c*(3*L^2-4*c^2)}{24*E*Ixc} + \frac{(R_{C1L}+R_{C2L})*c*(3*L^2-4*c^2)}{24*E*Ixc}$$

$$\Delta_1 = \delta_B - \delta_A \tag{7}$$

According to ISO and FEM standards; deflection design criteria Δ_1 and Δ_2 have been determined based on a maximum of 20 mm. Deflection (collapse) values obtained as a result of evaluating different loading conditions using analytical equations are compared in Table 3.

2.2.2. Ingot Crane Finite Element Linear Static Analysis Studies

The modeling process of the designed ingot process crane by making analytical calculations, in accordance with FEM and ISO standards, was carried out through Autodesk Inventor and SolidWorks package software programs. The 3D model with simplified geometry for the ingot crane beam system and trolley chassis is shown in Figure 5. All structural components of the beams have been selected with S355JR material, while a different type of steel, 42CrM4 (4140), has been chosen for the wheel and running gear assemblies. In evaluating stress examination, analysis scenarios were carried out by taking into account the critical regions and the yield strength limit of the respective material. In the finite element analysis method, the critical loading conditions were established with the crane system structural construction considering the load conditions of the first trolley (1.trolley) as 'unloaded (Q_L= 0 kg)' and Q_L load carried by the second trolley (2.trolley) as 35,000 kg (4m).
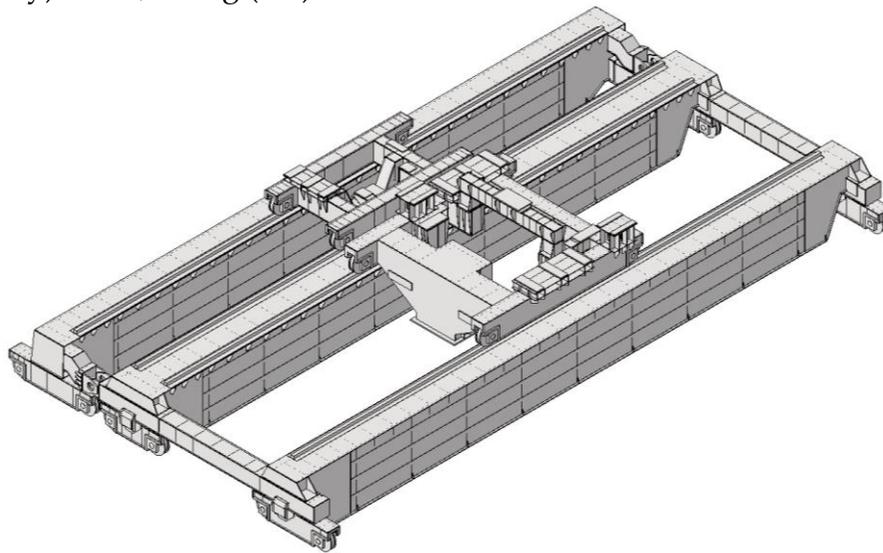

Figure 5. Ingot Crane 3D Model Study (Autodesk Inventor)

As part of the finite element analysis, a linear static analysis has been structured to obtain Von Mises stresses in critical areas and deflection values for individual beams. Figure 6 illustrates the support points and critical loading conditions for the ingot process crane. For the holding boundary condition, the connection bearings of each wheel have been determined as built-in, and Rx rotational freedom is provided for the bogie joint connecting section A and section B, where Ux = Uy = Uz = 0, Ry = Rz = 0. In addition, the loading boundary condition is provided while loading in the -Uy direction have been specified for the reducer supports, motor supports, and balance traverse. Moreover, gravity acceleration has also been defined in the simulation environment for the system. Figure 6 shows the ingot crane boundary conditions.
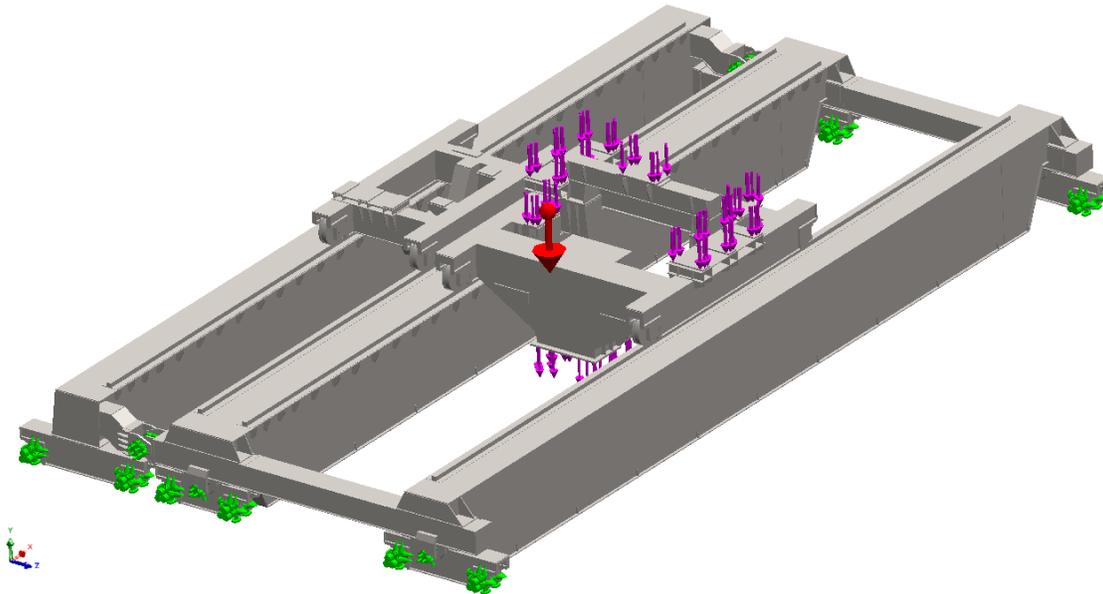
Figure 6. Representation of Support Points, Boundary Conditions, and Critical Loading Conditions for the Ingot Crane

Details of mesh parameters for the finite element linear static analyses of the critical loading condition of the ingot crane were determined as shown in Table 1. Depending on the components in the crane structural framework, mesh convergence was made in different loading scenarios and an optimal mesh distribution and node elements have been created with a mixed curvature-based meshing approach.

Table 1. Finite Element Analysis Optimum Mesh Details

Study name	INGOT FEA* (-Predefined-)
Detailed mesh type	solid mesh
Meshing approach	Mixed curvature based mesh
Jakobaen points for high quality mesh	16 points
Maximum element length	50 mm
Minimum element length	2,5 mm
Quality of mesh	High
Total number of Nodes	4781436
Total number of Elements	2295618
Maximum aspect ratio	39,024
Percentage of elements with aspect ratio less than 10	44,2
Percentage of elements with aspect ratio greater than 3	0,429
Percentage of deformed elements	0
Number of corrupted elements	0
Re-meshing failed parts independently	Close
Mesh completion time(hour:min:sec)	00:05:28
Computer's name	PROJE24

In terms of the general structure of the crane construction, the smallest element size in mesh convergence has defined as "2.5 mm". However, when critical areas are examined, the change in stress is determined not by the mesh element size, but by the number of elements and nodes surrounding the critical region. In this case, a mesh convergence optimization has been conducted for critical beam joint regions where the stress concentration is intense in the structure. In Table 2, both the maximum stress in the critical region and the overall deformation state of the system are given.

Table 2. Mesh Convergence Table for Critical Beam Joint Regions

Number of Mesh Around Circle of Beam Joint Area	σ_{max} (MPa)	δ_{mav} (mm)
25	234,5	8,27
20	234,5	8,27
16	227,5	8,27
10	225,6	8,24

Three different loading case scenarios have been determined for the three-girder carrier ingot crane beam system, which is a first in the literature (See Table 3). Based on these loading situations, linear static loading analyses have been conducted for the most critical conditions. In Figure 7, Figure 8, Figure 9 and Figure 10, visuals of the analysis results performed for the most critical loading case (unbalanced) using the linear static finite element analysis method are given.

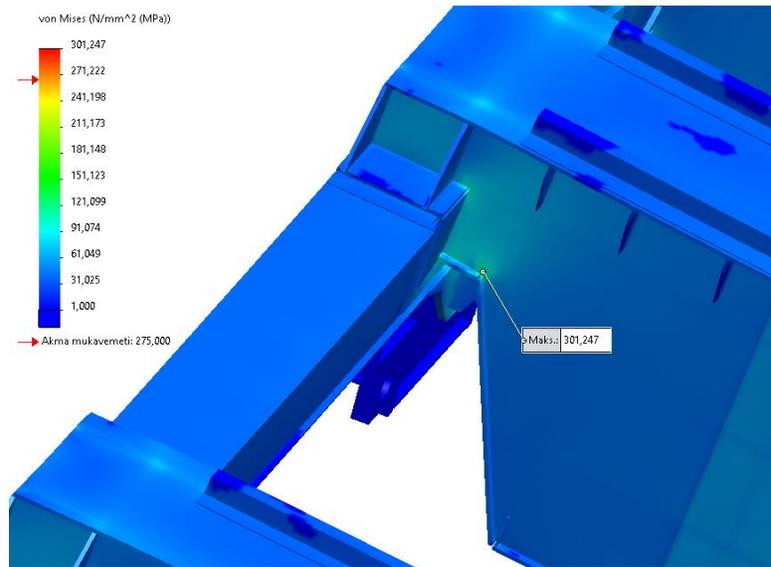*Figure 7. General Von Mises Critical Stress Condition for the Ingot Process Crane Carrier Bridge Beam*

Figure 8. Critical Von Mises Stress Region in the Contraction Section of the Carrier Bridge Beam
(σ=301.2 MPa)

The analysis results (σ=301.2 MPa<355 MPa) obtained by placing probes in the critical stress concentration areas occurring in the end regions where there is a geometric discontinuity is inherent in the design of the crane bridge beam geometry, as shown in Figure 8. The other critical stress regions are the trolley wheel bearings and bearing shafts (Figure 9), as well as the joint connections providing operational flexibility to the beam structures under loading conditions (Figure 10).
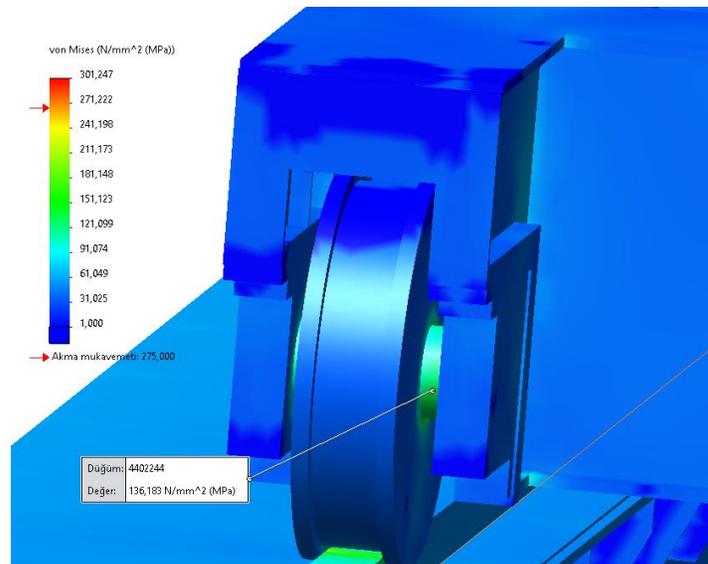

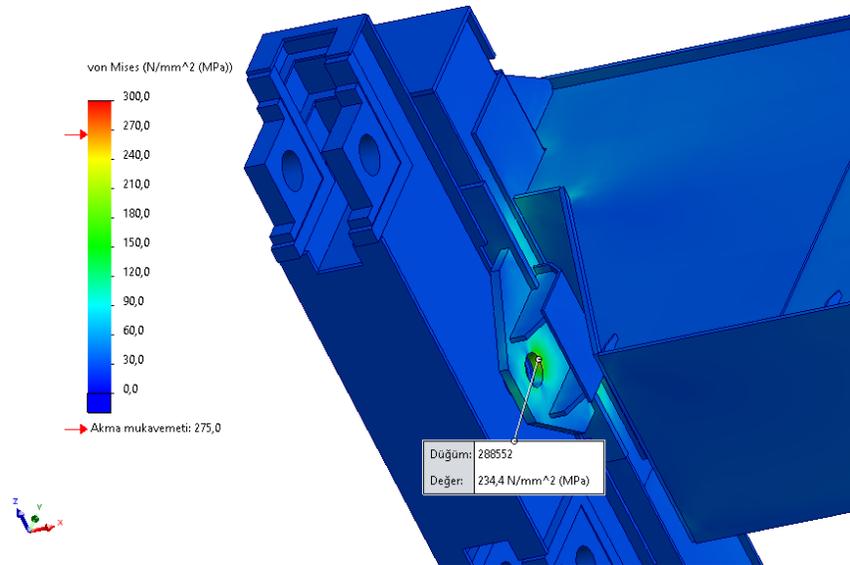*Figure 9. Von Mises Stress Conditions in the Trolley Wheel Bearings (σ=136.1 MPa)*

Figure 10. Critical Mises Stress Condition in Bogie Head Beam Bearings (σ=234.4 MPa)

Within the scope of the finite element analysis results carried out in this study, the deflection condition results for the ingot crane three-girder carrier system are given in Figure 11. In addition, the deflection (collapse) conditions obtained for three different critical loading boundary conditions determined in the study are compared in Table 3.
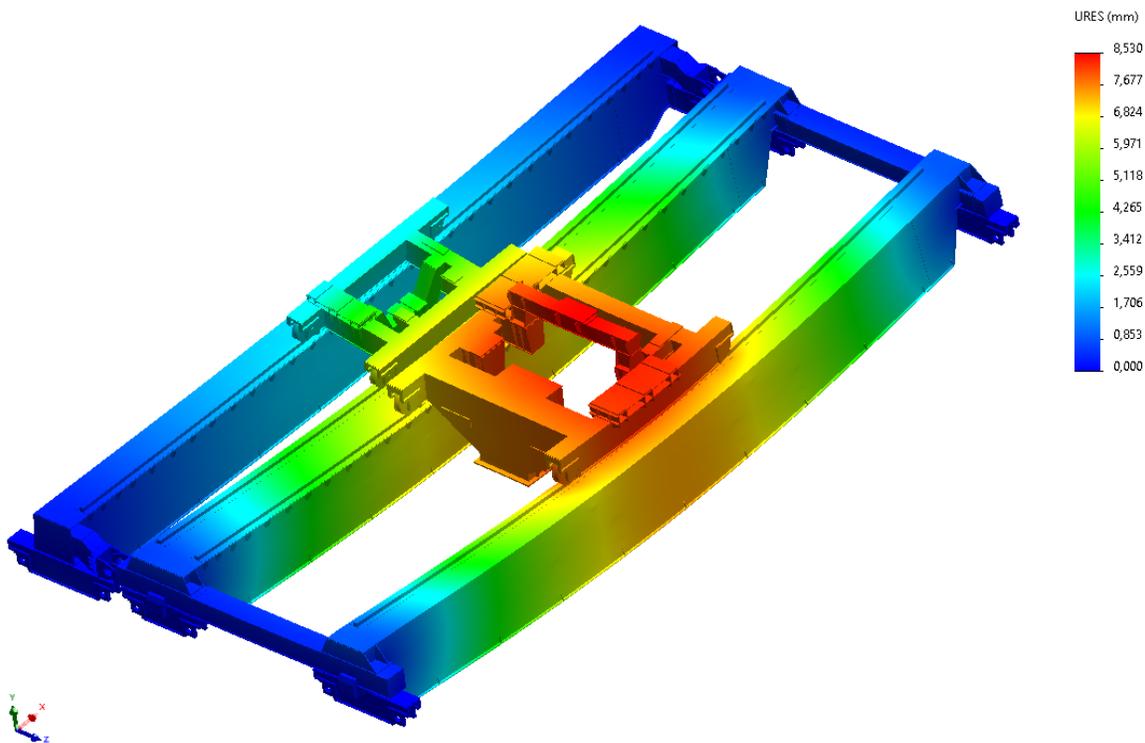

Figure 11. Ingot Crane Three-Girder System FEA Deflection (Collapse) Situation (δmax=8.5 mm)

The Safety Factor values for the entire integrated beam group and the critical overlap areas of the middle beam (Section B) are given in Figure 11 and Figure 12. When the results of the FEA are examined, the safety factor display panel (Figure 12) is configured for the 2-20 scale range due to the fact that the construction is highly secure. As a result of the analysis, it has been revealed that the safety factor value required by the standards is above the required safety factor value in the critical areas of the crane beams and that the safety factor is calculated as minimum 2 and above in these critical areas. In the full loading condition of the 2nd Trolley (35 tons, 4m) to perform the main ingot process, the maximum deflection (δmax) will occur in the beams (B and C beams). Therefore, in these critical regions, critical analysis studies have shown that the local safety factor is calculated to be above 3.8.
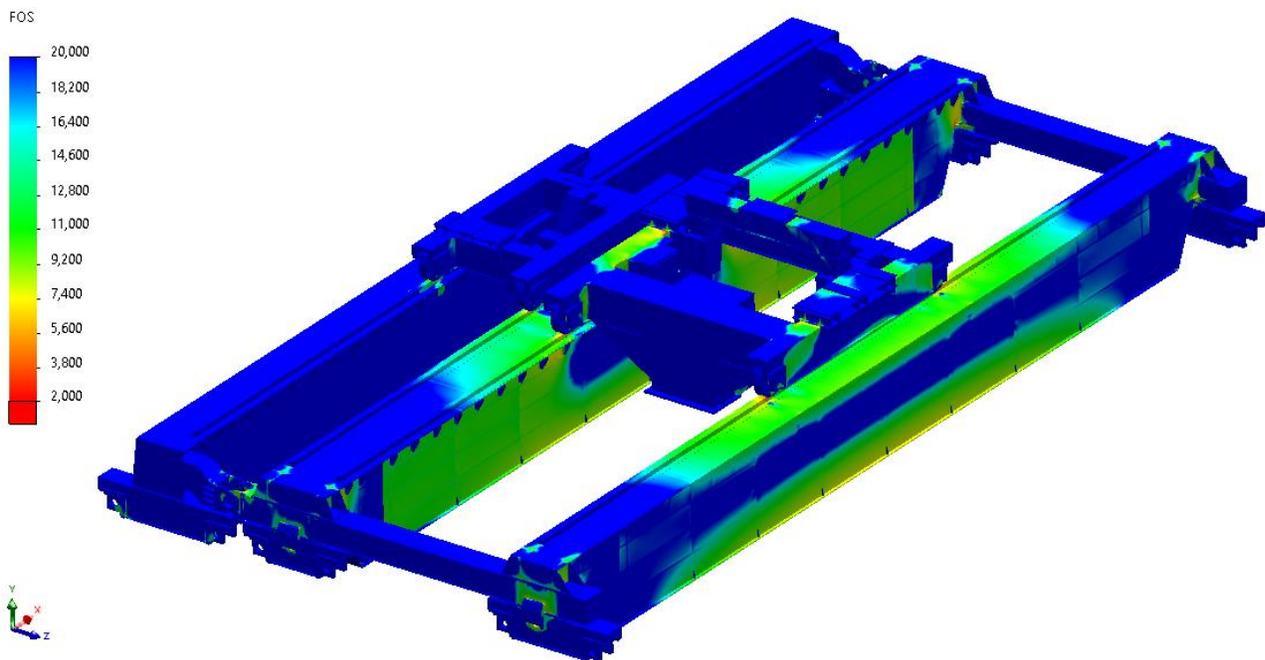

Figure 12. Safety Factor of the Ingot Crane Critical Loading Condition (S.F.:2~20)

As a result of the analysis, the region where the most intense and highest stress occurred has been identified as the end regions of the crane beams where geometric section narrowing occurred (Figure 8). The stress generated in this region has been obtained as 301.2 MPa according to the analysis results. Although stress occurs below the yield strength, the implementation of an ideal weld seam that minimizes the possibility of notch effects, which are not visible in the model but may occur in end regions with existing section narrowing, strongly eliminates the likelihood of any adverse effects in undesirable situations. Furthermore, when the crane structure system is considered as a whole, it has been determined based on FEA that the maximum stress values in other critical regions (Figure 9 and Figure 10) are quite low.

3.   Results

In the scope of the design and analysis of ingot process crane, deflection (collapse) has been determined as the design criterion for the three-girder carrier system and deflection conditions for each beam under different loading scenarios have been determined both through analytical calculation methods and finite element analysis.

It has been determined through the analysis that the safety factor value in critical areas of the crane beams exceed the required safety factor value in accordance with national and international standards and was calculated as minimum 2 and above (2~20) in these critical areas.

Table 3. Deflection Values of Beam Types Based on Loading Conditions

Loading Boundary Conditions		Analytical Approach			Finite Element Analysis (FEA)			%Difference		
		δ_A (mm)	δ_B (mm)	δ_C (mm)	δ_A (mm)	δ_B (mm)	δ_C (mm)	δ_A (%)	δ_B (%)	δ_C (%)
1. Analysis Case (No Load Condition)	Beam Self Weight and Trolley, Hook, Rope Loads $[Q_G + Q_T]$	2,6	6,6	6,5	2,15	6,1	5,76	%21	%%7	%12
2. Analysis Status (Full Loading Status)	Maximum Upload Status $[Q_G + Q_T + Q_L]$	6,85	11,0	9,1	6,40	9,9	8,10	%7	%11	%12
3. Analysis Status (Unbalanced)	* Critical Upload Status $[Qcr][Q_{cr}]$	2,6	9,1	9,6	2,15	8.3	8,4	%21	%10	%13
*: Loading conditions were applied for car no. 1 $(Q_G + Q_T)$ and for car no. 2 $(Q_G + Q_T + Q_L)$. *: Load multiplier coefficient according to DIN15018: 1.22 is taken as basis.										

Design deflection criterion for beams is given in equation 7; in case of critical loading condition, values calculated through analytical approach and FEA are Δ_1= 6.5 mm and Δ_2= 6.15 mm, respectively (Table 3). These values are less than the 20 mm deflection value specified in the standards and critical design boundary condition. Additionally, values of Δ_1 and Δ_2 obtained in calculations for other loading conditions are also smaller than these calculated values.

In this study, critical stress concentrations occurring in the end regions where geometric discontinuity exists due to the ingot process crane bridge beam geometry design has been determined as 301.2 *MPa*. When the FEA analysis results were examined, it is observed that there is no significant high stress leading to yield strength throughout the general ingot crane beams. As a result, it has been concluded that the deflection values obtained

as a result of both analytical approaches and finite element analysis conducted with FEA fully meet the specified optimum design criteria in the defined boundary conditions.

In the design processes, internationally recognized FEM, ISO, and EN 13001 standards have been taken as references [7]. With the design and initial prototype production of the "New Generation Ingot Crane" specific to the ingot process in the operational manufacturing process of the customer organization, both radical product innovation and production process innovation have been successfully accomplished by the BVS R&D Center, and the prototype product continues to provide seamless service. Furthermore, the beam section designs within the main frame design of the ingot crane, as well as the 360° rotating column-mounted double-jaw gripper attachment, have been transferred to the knowledge base and know-how pool of BVS Cranes, contributing to value-added initiatives. Figure 13 depicts the prototype next-generation ingot crane that continues to serve at Asil Steel customer organization.
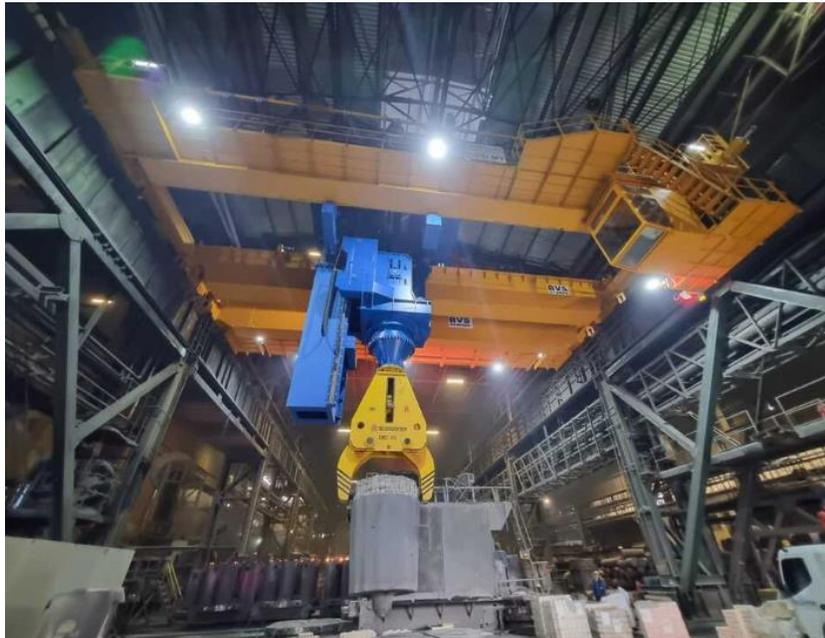

Figure 13. Prototype of the Next-Generation Ingot Crane (Asil Steel) [8,10]

4.   Discussion and Conclusion

Nowadays, the importance of radical and gradual innovation concepts under the topic of innovation management has been increasing day by day, and sustainable innovation policies are crucial for organizations in the industry. In this regard, the continuous improvement of products and service expectations with specific processes tailored to customer organization's needs and the development of next-generation products and services in along with technological advancements has become an indispensable motto

of manufacturers in the changing market and competitive environment in the crane industry. From this perspective, the crane and ingot production industry, which perform specific design processes and operational production processes, will contribute to a positive contribution in increasing competitiveness in terms of work and occupational safety, as well as labor and other costs. With the success story of the ingot crane realized within the scope of this study, it has secured its place in the global market in terms of both export capabilities and import substitution, especially for the ingot casting industry, not only in our country but also worldwide.

From a technical point of view, the ingot cranes serving in the industry have been manufactured with four-beam cranes. However, the new ingot crane that designed and produced within the scope of the project has been configured with a three-girder and the prototype has been manufactured. It has been concluded that the new generation ingot crane meets the design criteria both in terms of stress and deformation (collapse).

In addition, due to the specific innovations and process-based competencies it encompasses in terms of hardware and capabilities, a patent application has been made to the Turkish Patent Institute (TPE) with the application number 2023/002382 and the process is at the examination and research report stage by the institution.

5. Acknowledge

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