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Original Research Article

Study of the Effect of Connection Stiffness on Structural Systems and Theire Structural Integrity

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Abstract

Structural systems consist of sub-systems and elements. Connection elements are needed for the subsystems and assembly and integration of these systems to the main system. Because the main system can fulfill its functional tasks when its assembly and integration with the subsystem is completed. Systematic static strength and dynamic behavior of structures, load bearing material and static cross-sectional properties as well as the strength and stiffness properties of the connections have a significant effect. The effect of the stiffness of the connection elements is higher in thin structural systems where the cross-sectional dimensions are much lower than the system dimensions. Assembly and integration are provided by using connection elements also in thin structural systems such as steel structure, scaffolding and rack structures. Therefore, the strength and stabilization of corner connections and fixing elements affect the entire system. However, while making systematic calculations, the structures, staying on the safe side, are modeled with rigid or rotatory hinged approach. When the connections are modeled as rotatory hinges, larger cross sections are required and support elements are added to prevent the system from becoming kinematic and collapse. With this approach, in buildings that require a lot of connection elements, the weight of the building increases too much and thus the cost increases. On the other hand, when the system is modeled with rigid approach, since the joints are unnecessarily excessively safe and the system's elasticity is very low, sudden overloads may result in collapse accidents and cause loss of life. For this reason, connection elements, especially in thin structures, must be modeled with real stiffness values and verified by tests under the prescribed loads. The purpose of this research is to examine the structural system design approach by modeling thin structure connection elements realistically and to create sensitivity in this regard. With this modeling method, it is aimed both to reduce costs and to prevent possible accidents caused by wrong modeling.

Keywords: Connection elements, connection stiffness value, scaffolding and rack structures, lightweight structure design.

INTRODUTION

Twelve percent of all work accidents in our country and 34 percent of work accidents that result in death occur in construction workplaces. 38 percent of the accidents in the construction works are experienced by falling down from height, and 25 percent of falling down from height is experienced in the facade scaffolding. This shows us the importance of scaffolding safety. Therefore, connection elements are of great importance in the design of systems such as scaffolds to ensure the safety of the structure. In the study titled Facade Scaffolds in terms of Occupational Health and Safety published by the Ministry of Labor and Social Security under the Safe Scaffold Project, the number of accidents experienced in terms of occupational safety was statistically given in detail and the importance of the issue was emphasized in terms of occupational health [1]. In this study, it will be emphasized on the important criteria in the selection of connection elements to protect the system integrity in a theoretically designed frame, rack and scaffold system. In the conceptual design phase, it will be mentioned about the method to be followed in subjects such as the degree of freedom of the connections of the structures and the determination of the fixing points. What the connecting elements should be can be selected in the light of the information obtained by the created method.

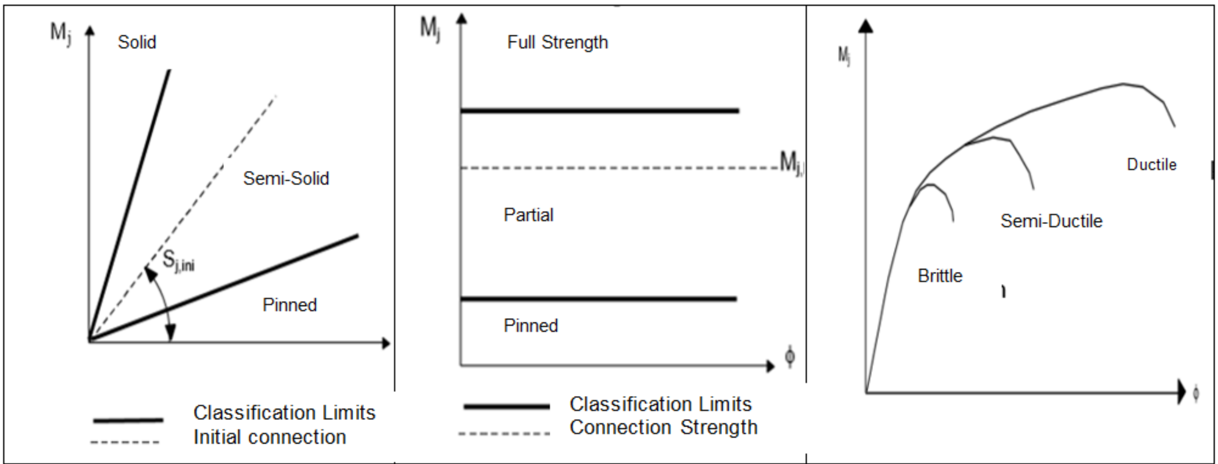
Structural responses in a system are directly related to displacements, internal forces occurring in the system, and the type and size of the load externally applied to the system. A structure must provide the following 4 steps to ensure its structural integrity;

1) Correct characterization of the structure,
2) Correct classification of the structure,
3) Proper modeling of the structure,
4) Idealization of the structure.

In order to properly characterize the structure, regardless of the type of material to be used, all system and sub-system elements should be selected in a way that is suitable for the purpose of use so that the structural integrity is not impaired.

The correct classification of the structure is related to the stiffness, strength and ductility of the system. Ways of classifying structures is emphasized in EUROCODE3 [2]. Stiffness of the system in accordance with the intended use of the structure is determined as: a rigid, semi-rigid or pin connection. In structures such as scaffolding, the system design takes place as semi-rigid since the classification of the system as rigid causes sudden collapses in the system in sudden loading cases. However, in structures such as satellite, high stiffness is required in order to prevent the functional properties of the sensitive electronic components on the system from being affected by structural vibrations.

M(moment)-φ(angular rotation) graphs in Figure 1 show the limits of the stiffness, strength and ductility range that will be defined in order for a system to operate without collapsing.



a) Classification-1 (Stiffness)	b) Classification-2 (Strength)	c) Classification-3 (Ductility)

Fig-1: Classification of a structural system

After the characterization and classification of the system has been made, the full modeling of the system must be ensured by defining the connection elements fit for the purpose. In this context, type of the connection element to be used should be chosen taking into account the degrees of freedom defined for the system. Finally, the system should be modeled in the most realistic way by making the system idealization [2].

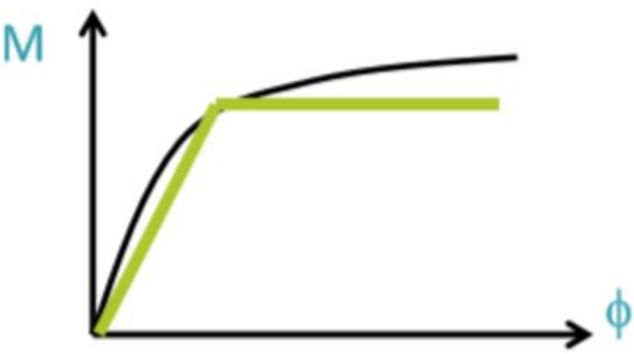


Fig-2: Idealization of a structural system

The correct modeling of a connection element is very important in order to correctly determine the mechanical behavior of the structure. The connection types to be used in the modeling of the structures are summarized as in Table 1 considering the stiffness and strength values [2].

Table-1: Connection types to be used in modeling according to the classification of structures

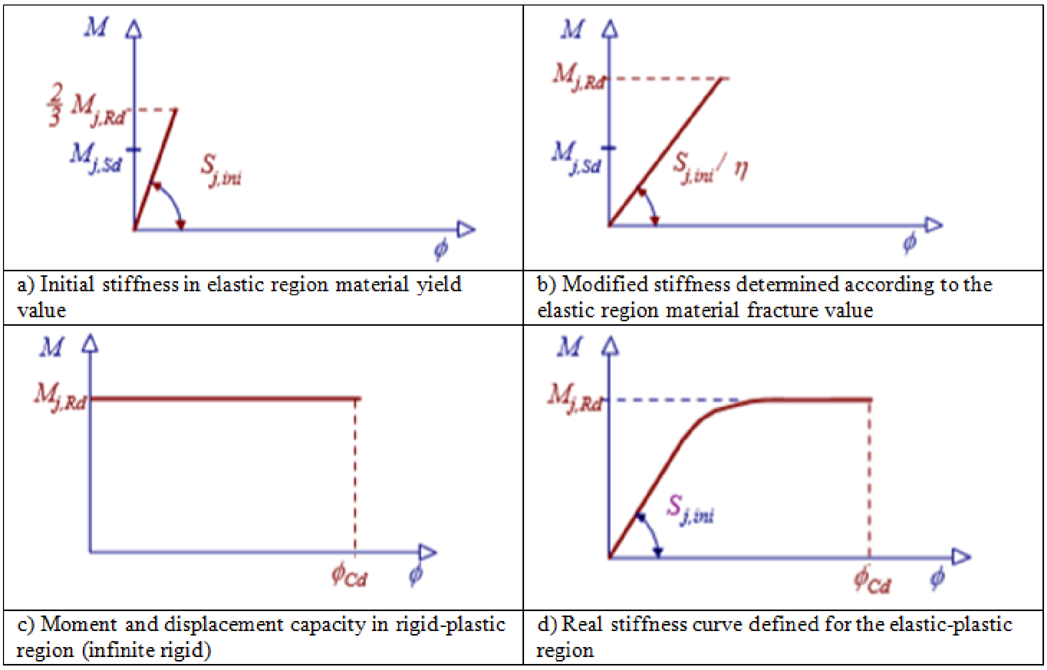
STIFFNESS	STRENGTH		
	Full Strength	**Partial Strength**	**Pinned**
Rigid	Continuous*	Semi-Continuous**	-
Semi-Rigid	Semi-Continuous	Semi-Continuous	-
Pinned	-	-	Easy***

*Axial and rotational freedoms are limited
**Axial and rotational freedoms are partially limited
*** Free to rotate in specified directions

Table -2: Classification of analysis types according to connection types

CONNECTION MODEL	ANALYSIS TYPE		
	Elastic Analysis	**Rigid-Plastic Analysis**	**Elastic-Plastic Analysis**
Continuous	Rigid	Full Strength	Rigid/Full Strength
Semi-Continuous	Semi-Rigid	Partial Strength	Rigid/Partial Strength
			Semi-Rigid/Full Strength
			Semi-Rigid/Partial Strength
Easy	Pinned	Pinned	Pinned

According to Table 2, for elastic analysis of a framing structure, it is sufficient to check only the stiffness value. The strength and rotational capacity of a connection must be checked for rigid-plastic analysis. For all other cases, stiffness and strength parameters should be included in the connection model [3]. According to the connection types used, the elements to be used in the system should be selected by obtaining the Moment-Rotation graphs in Figure 3.



a) Initial stiffness in elastic region material yield value
b) Modified stiffness determined according to the elastic region material fracture value
c) Moment and displacement capacity in rigid-plastic region (infinite rigid)
d) Real stiffness curve defined for the elastic-plastic region

Fig-3: Determination of system loads according to stiffness values

If the stiffness of a connection element designed for the plastic region is known, the behavior of the system in the plastic region can be examined by using this value in the elastic analysis. In this way, more realistic values are obtained [2].

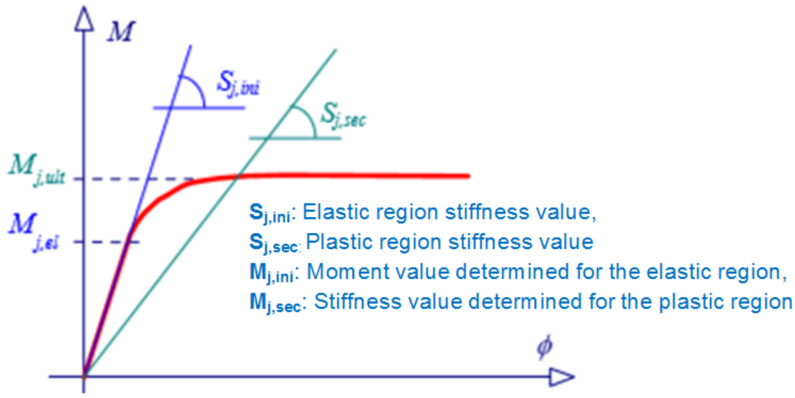


Fig-4: Determination of the stiffness value to be used in the elastic analysis type to determine the behavior of the structure in the plastic region

Iuliana PISCAN *et al*. examined the force-stiffness variation in the system under variable stiffness values for the modeling of bolts in their studies and managed to achieve nonlinear results in a linear model. They concluded that the force exerted on the bolts did not change after a certain stiffness value. This shows that a modeling that will enable design in the plastic region can be obtained with the result of elastic analysis [3].

J. MAREŠ *et al.* compared the test results with the stiffness curve obtained according to the results of the analysis made in the elastic region in a study on sandwich panels. As a result, they found that the estimated stiffness value obtained in the elastic region remained much higher according to the test results in the plastic region. This study shows that the safety factor of the products designed according to the results of the analyzes made according to the elastic region is very high [4].

In the study of Jerome Montgomery, he found that the displacement results obtained by using RBE2, beam and rigid elements for bolt modeling are close to each other. The study shows that using suitable stiffness values for beam elements will give correct results [5].

M.E. Kartal *et al*. emphasized the importance of semi-rigid connection modeling in structures by making a detailed study on rigid, semi-rigid and pinned systems in their studies [6].

In their study on concrete structures, Marcela N. Kataoka et. al. emphasized that controlling only the stiffness value of the system is not sufficient for the safety of the construction, but also controlling other parameters is necessary for structural integrity [7].

Turkish Standards Institution has standards published for designed scaffolding structures and systems. While TS EN 12810-1 mentions the product properties of the facade scaffolding consisting of precast components, TS EN 12810-2 mentions special structural design methods. In addition, TS EN 12811-1 mentions performance requirements and general design criteria, TS EN 12811-2 mentions material information and TS EN 12811-3 mentions load tests. The requirements specified by TSE should be taken into consideration at all stages of the designed scaffolds, from the conceptual design stage to the production and testing activities [8].

In addition, the effect of wind loads on the structure during the design phase in high structures should be checked in terms of system strength both statically and dynamically. In relation to that, in a study based on Eurocode3, E. Şafak modeled the wind speed and pressure numerically and calculated the wind loads affecting the buildings [9]. In addition, characteristic loads (permanent loads, moving loads, snow, ice and wind loads) affecting the structures are specified in TS498-1997 and TS ISO 9194-1997 standards. In the 2007 Earthquake Regulation, earthquake loads are mentioned. Seminar notes on “Design, Calculation and Construction Principles of Steel Structures” published by S. Güvensoy mention the calculation methods of the loads that should be taken into consideration in the design of the constructions [10].

METHODOLOGY

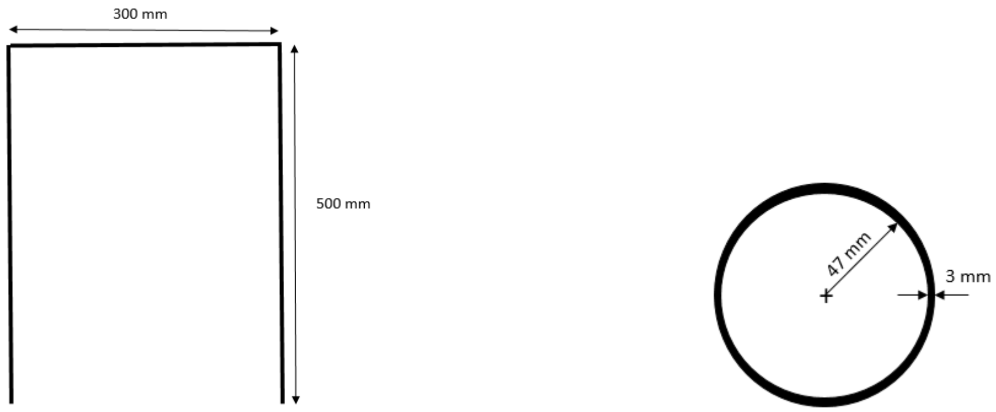
In this study, the mechanical behavior of frame structures, framing and rack systems are examined in relation to the modeling of connection elements. In this context, the following system parameters have been controlled for each model;

Table-3: Parameters examined for the designed mechanical systems

Mechanical System	Parameters Examined
Frame Structure	Moment Vectors
Scaffolding Structure	Force/Displacement Curves
Rack Structure	Force/Displacement Curves Moment/Rotation Charts Rotation/Stiffness Charts

1) System Design and Analysis Results for Frame Structure

The dimensions and cross-section dimensions of the system determined for the frame structure are given in Figure 3. The structure was modeled using finite elements analysis program and in order to obtain distributed moments and forces on the system, a total of 130 1-dimensional CBEAM elements were used. AL7050 was used as material. The elasticity of the system is taken as 71700 MPa, the poisson ratio is taken as 0.33 and the density is taken as 2.83e-06 kg/mm^3.



(a) (b)

Fig-3: Sample case model for frame structures; a) Geometrical dimensions of the formed frame structure b) Cross-sectional dimensions of the elements used

In the modeling of the frame structure, a total of 6 configurations located in Figure 4 were used. The degrees of freedom in the frame legs are defined as Nod1 and Nod2, and the degrees of freedom in the connections above are defined as Nod3 and Nod4. The degree of freedom in Nod1 and Nod2 is defined by the Single Point Constraint. In addition, a single point constraint is given to Nod3 in the z direction. For each configuration, 1000N force (F) to the structure was applied in the directions shown in Figure 4. For Nod3 and Nod4 connection, CBUSH elements were used to allow the stiffness values of the elements in 6 directions and to see their movements relative to each other.

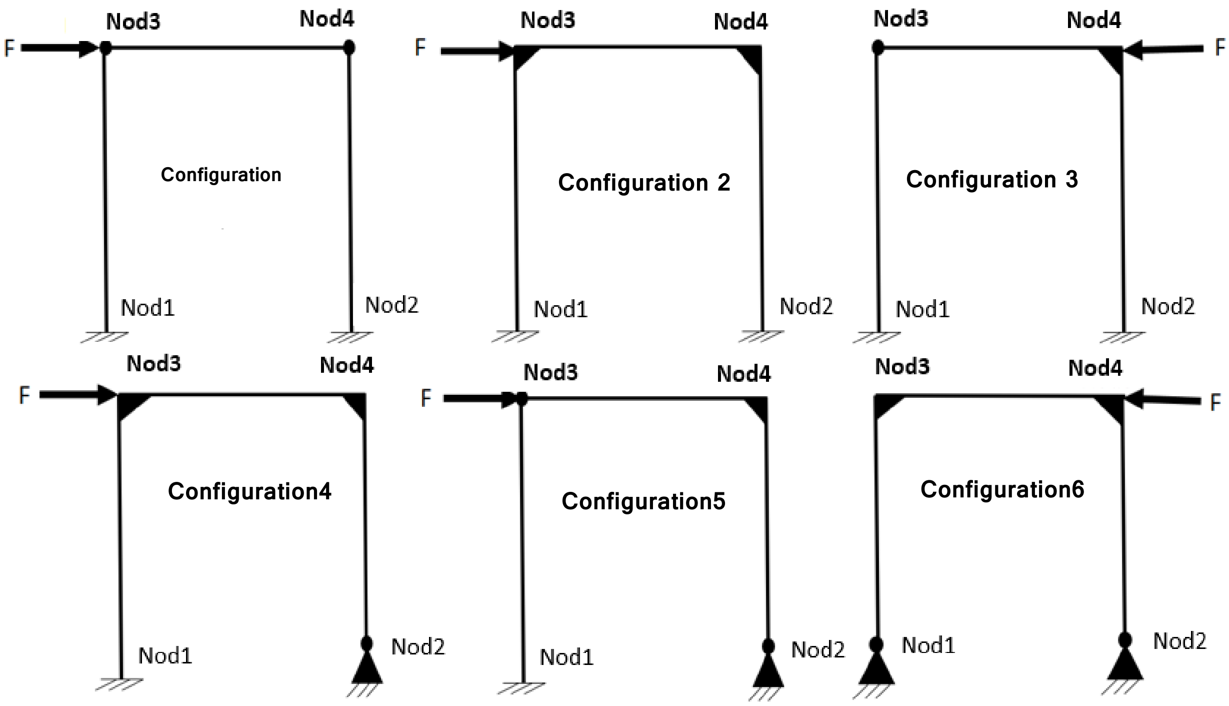


Fig-4: Different types of configurations used in modeling the frame structure

Connection freedom degrees determined for each configuration type are defined in Table 4.

Table-4: Connection Freedom Degrees Used in Frame Structure

FRAME CONFIGURATION 1				
	Nod1	**Nod2**	**Nod3**	**Nod4**
Point-fixed Connection Degrees of Freedom	1,2,3,4,5,6	1,2,3,4,5,6	1,2,3	1,2,3
FRAME CONFIGURATION 2				
	Nod1	**Nod2**	**Nod3**	**Nod4**
Point-fixed Connection Degrees of Freedom	1,2,3,4,5,6	1,2,3,4,5,6	1,2,3,4,5,6	1,2,3,4,5,6
FRAME CONFIGURATION 3				
	Nod1	**Nod2**	**Nod3**	**Nod4**
Point-fixed Connection Degrees of Freedom	1,2,3,4,5,6	1,2,3,4,5,6	1,2,3	1,2,3,4,5,6
FRAME CONFIGURATION 4				
	Nod1	**Nod2**	**Nod3**	**Nod4**
Point-fixed Connection Degrees of Freedom	1,2,3,4,5,6	1,2,3,4,5	1,2,3,6	1,2,3,4,5,6
FRAME CONFIGURATION 5				
	Nod1	**Nod2**	**Nod3**	**Nod4**
Point-fixed Connection Degrees of Freedom	1,2,3,4,5,6	1,2,3,4,5	1,2,3	1,2,3,4,5,6
FRAME CONFIGURATION 6				
	Nod1	**Nod2**	**Nod3**	**Nod4**
Point-fixed Connection Degrees of Freedom	1,2,3,4,5	1,2,3,4,5	1,2,3,4,5,6	1,2,3,4,5,6

Fig-5 Shows the global axis set used in the finite element model.

Axial	x	1
	y	2
	z	3
Rotational	Rx	4
	Ry	5
	Rz	6

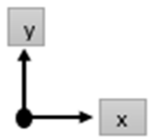
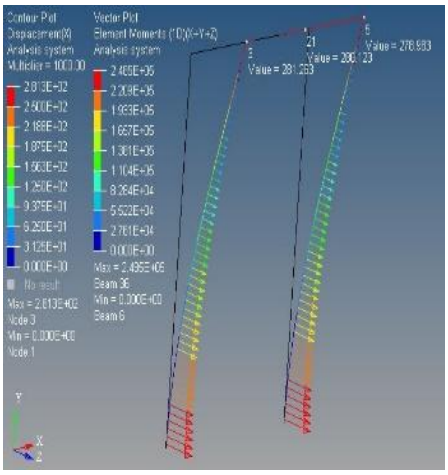
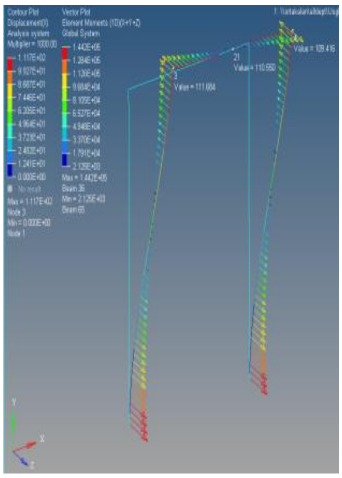


Fig-5: Degrees of freedom used in the frame model

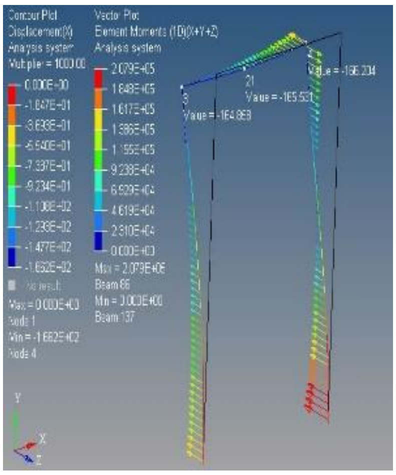
In the finite element analysis, the behavior of the system under the force applied at the determined points was examined by using the linear static analysis method. The results are shown in Figure 6.



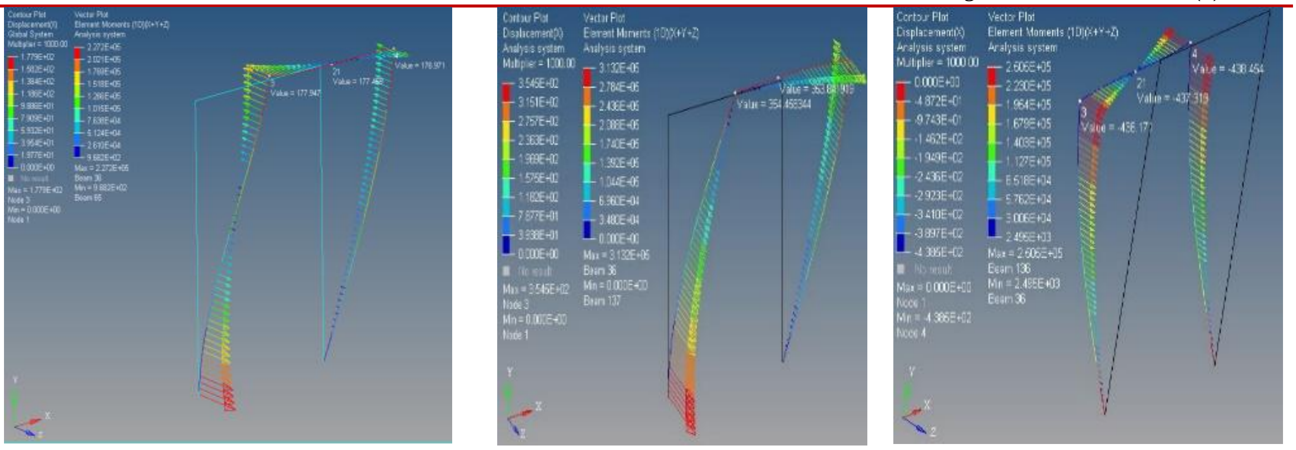
a) Configuration 1



b) Configuration 2



c) Configuration 3



d) Configuration 4 e) Configuration 5 f) Configuration 6

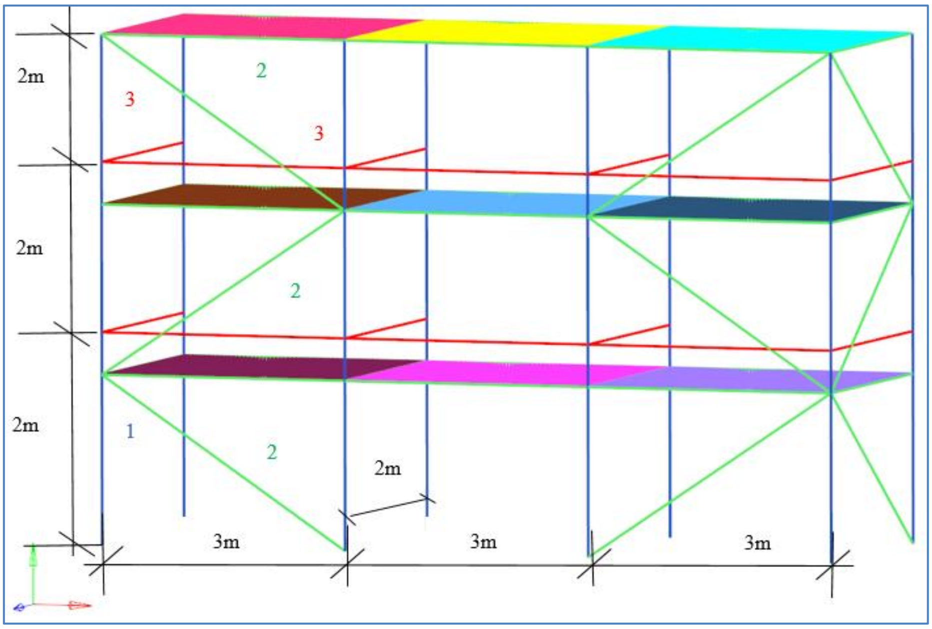
Fig-6: Frame model linear static analysis results

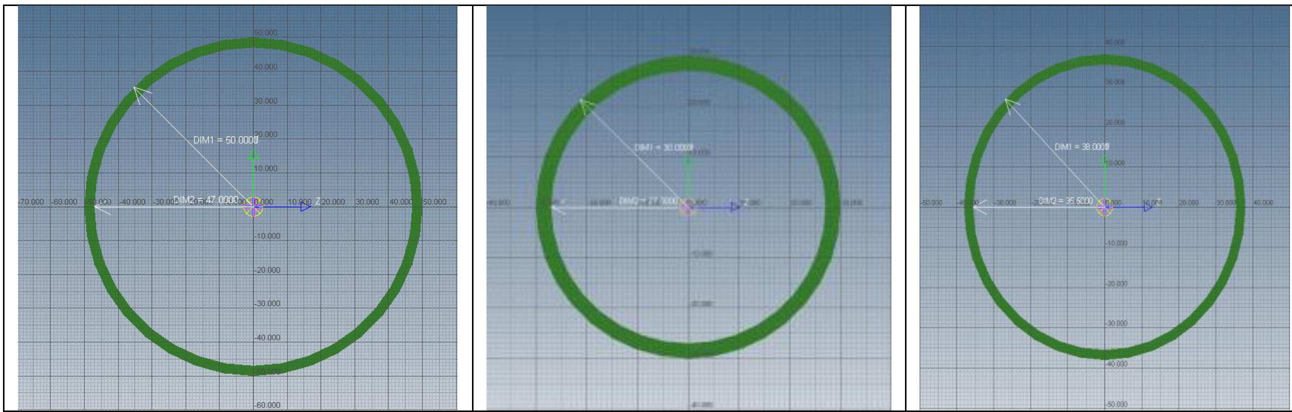
Table-5: Frame model linear static analysis displacement, force stiffness results

FRAME CONFIGURATION 1				
	Nod1	**Nod2**	**Nod3**	**Nod4**
Point-fixed Connection Degrees of Freedom	1,2,3,4,5,6	1,2,3,4,5,6	1,2,3	1,2,3
Displacement (mm)_x	0	0	0.281	0.279
Single Point Constraint Forces (N)_x	-502.034	-497.966	0	0
Stiffness_x (N/mm)			1.786.598	1.784.824
FRAME CONFIGURATION 2				
	Nod1	**Nod2**	**Nod3**	**Nod4**
Point-fixed Connection Degrees of Freedom	1,2,3,4,5,6	1,2,3,4,5,6	1,2,3,4,5,6	1,2,3,4,5,6
Displacement (mm)_x	0	0	0.112	0.109
Single Point Constraint Forces (N)_x	-504.559	-495.441	0	0
Stiffness_x (N/mm)			4.504.991	4.545.330
FRAME CONFIGURATION 3				
	Nod1	**Nod2**	**Nod3**	**Nod4**
Point-fixed Connection Degrees of Freedom	1,2,3,4,5,6	1,2,3,4,5,6	1,2,3	1,2,3,4,5,6
Displacement (mm)_x	0	0	-0,165	-0,166
Single Point Constraint Forces (N)_x	294.259	705.741	0	0
Stiffness_x (N/mm)			1.783.388	4.251.452
FRAME CONFIGURATION 4				
	Nod1	**Nod2**	**Nod3**	**Nod4**
Point-fixed Connection Degrees of Freedom	1,2,3,4,5,6	1,2,3,4,5	1,2,3,6	1,2,3,4,5,6
Displacement (mm)_x	0	0	0.178	0.177
Single Point Constraint Forces (N)_x	-786.752	-213.248	0	0
Stiffness_x (N/mm)			4.419.955	1.204.791
FRAME CONFIGURATION 5				
	Nod1	**Nod2**	**Nod3**	**Nod4**
Point-fixed Connection Degrees of Freedom	1,2,3,4,5,6	1,2,3,4,5	1,2,3	1,2,3,4,5,6
Displacement (mm)_x	0	0	0.354	0.353
Single Point Constraint Forces (N)_x	-632.683	-367.317	0	0
Stiffness_x (N/mm)			1.787.240	1.040.558
FRAME CONFIGURATION 6				
	Nod1	**Nod2**	**Nod3**	**Nod4**
Point-fixed Connection Degrees of Freedom	1,2,3,4,5	1,2,3,4,5	1,2,3,4,5,6	1,2,3,4,5,6
Displacement (mm)_x	0	0	-0,436	-0,438
Single Point Constraint Forces (N)_x	498.909	501.091	0	0
Stiffness_x (N/mm)			1.144.287	1.144.043

2) System Design and Analysis Results for Scaffolding Structure

Scaffolding structures are often used in construction. The dimensions of the scaffolding structure used in this study and the cross section of the elements used in the system are as shown in Figure 7. The structure is modeled with CBEAM elements using finite element analysis program. All connections are created with CBUSH elements, and only the stiffnesses in the directions 1, 2, 3 are assigned with values. Displacement/stiffness graphics were obtained by changing these values between 1.0e+05 N/mm and 1.0e+13 N/mm AL7050 was used as material.





a) Cross Section 1	b) Cross Section 2	b) Cross Section 3

Fig-7: Sample case model for scaffolding structures and scaffold model design details

The loads shown in Figure 8 were applied to the scaffold structure vertically and horizontally simultaneously. Horizontal loads represent horizontal forces that can occur in the case of wind, while vertical forces represent vertical loads to act on the scaffolding structure. In the points where force is applied, RBE3 elements are used to distribute the applied load along the elements. Single point constraints applied to scaffolding legs are shown in Figure 8. Linear static analysis was performed to see displacement outputs depending on the loads in the system.

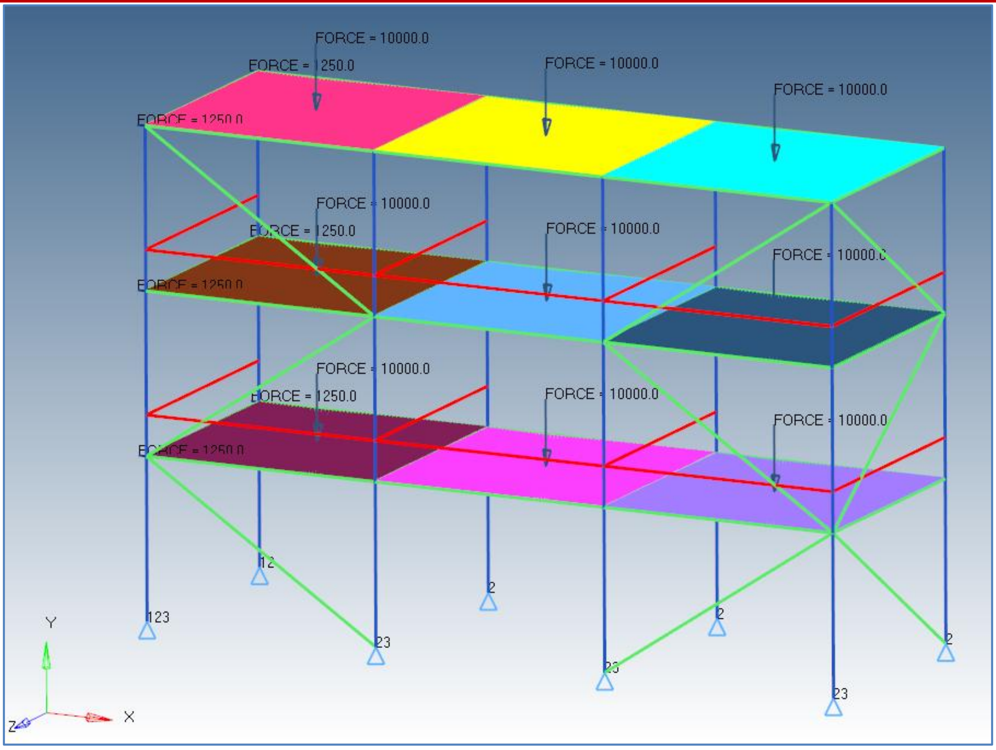


Fig-8: Scaffolding structure leg connection constraints and loads applied in vertical/horizontal direction

Figure 9 shows the linear static analysis results for the scaffolding structure. Graphs were drawn according to the stiffness values of the maximum displacements obtained in the X, Y and Z directions and were interpreted in the results section.

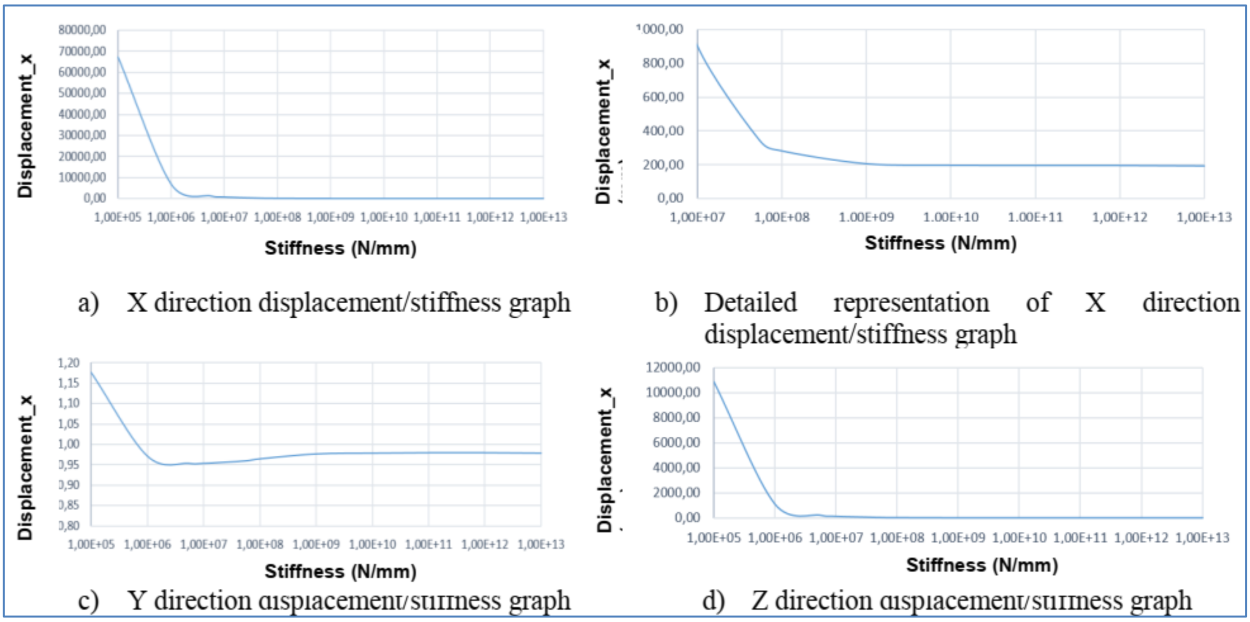


Fig-9: Force/displacement graphs of the scaffold structure obtained by linear static analysis

3) System Design and Analysis Results for Rack Structure

Rack structures are generally used to store items in warehouse areas. The dimensions of the rack structure used in this study and the cross section of the elements used in the system are as shown in Figure 10. The structure is modeled with CBEAM elements using finite element analysis program. All connections are created with CBUSH elements, and only the stiffnesses in the directions 1, 2, 3 are assigned with values. By changing these values between 1.0e-01 N/mm and 2.09e+10 N/mm, displacement/stiffness and moment/rotation graphics were created. AL7050 was used as material.

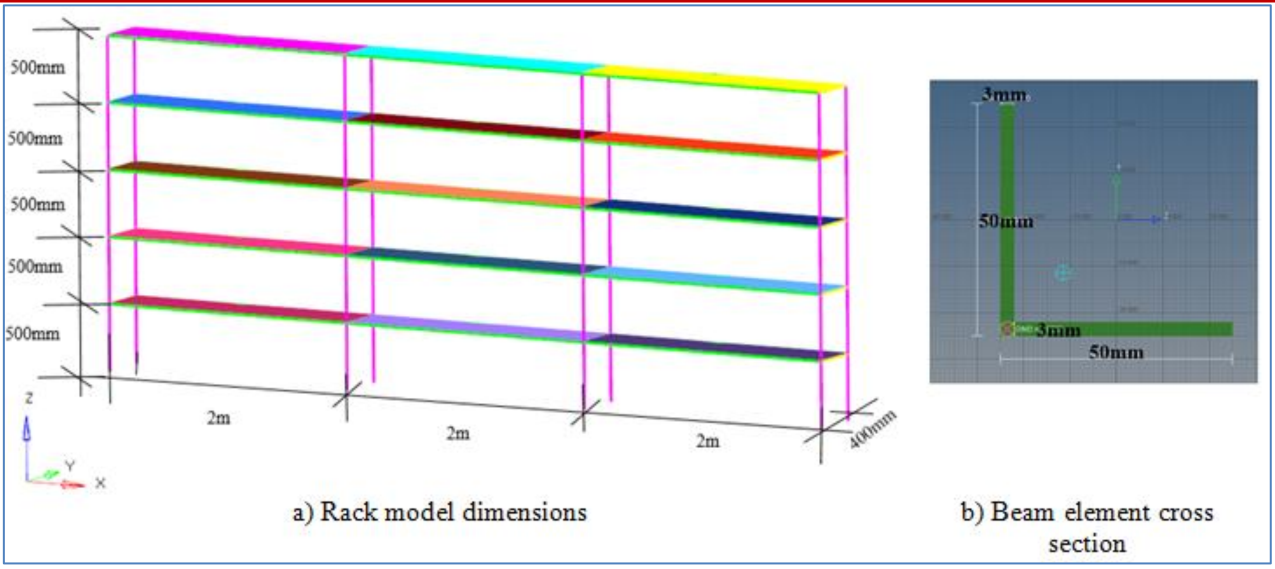


Fig-10: Sample case model and rack model design details for rack structures

The loads (600N) shown in Figure 11 are applied to the rack structure vertically. The perpendicular forces represent the loads to act on the rack structure. In the points where force is applied, RBE3 elements are used to distribute the applied load along the elements. The single point constraints applied to the rack legs and wall fixing points are shown in Figure 11. Linear static analysis was performed to see displacement outputs depending on the loads in the system.

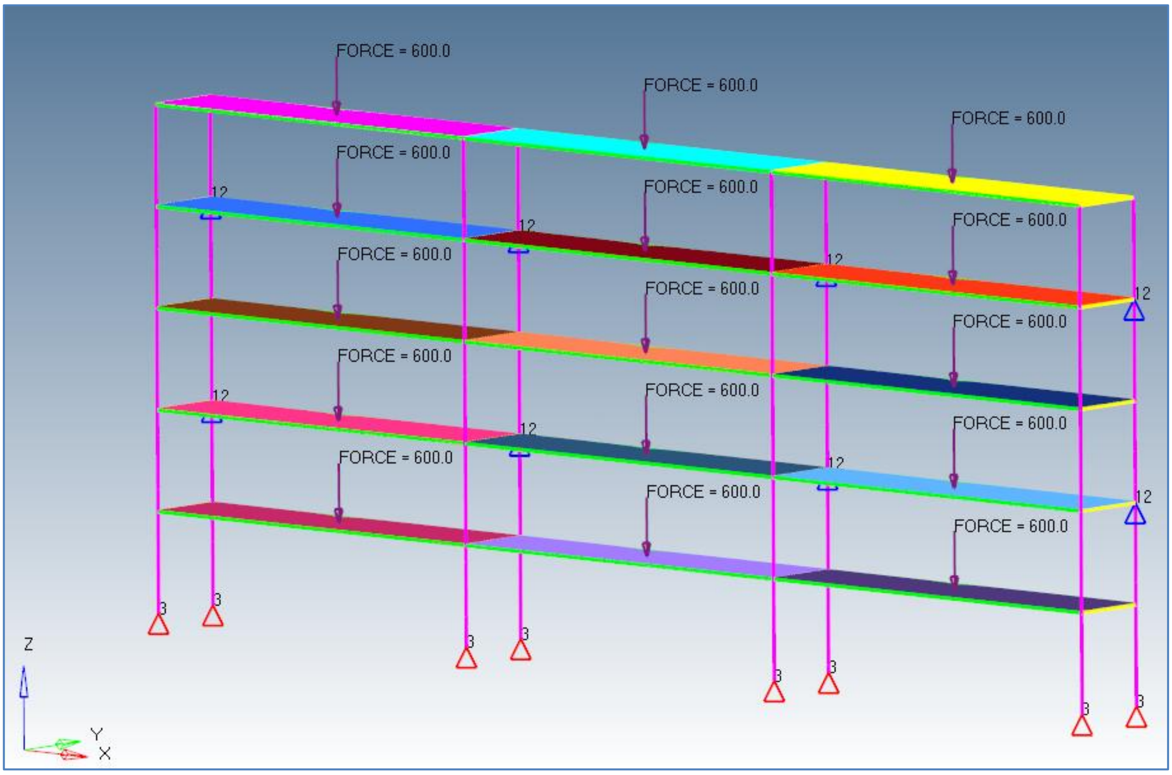


Fig-11: Rack structure leg/connection constraints and loads applied in vertical direction (It is drawn for the circled connection in Figure 12 and Figure 13.)

Table 6 shows the moment and rotation values corresponding to the variable stiffness values of the connections. Figure 12 and Figure 13 include the results of linear static analysis performed for rack structure. Graphs of maximum displacement/stiffness obtained in the x direction and moment/rotation - rotation/stiffness graphs in the y direction are drawn and the graphs are interpreted in the results section.

Table-6: Moment/rotation values corresponding to variable connection stiffness values

Moment (Nmm)			Max Dönme (^{0})			Katılık (N/mm)
X	Y	Z	X	Y	Z	
2,81E+03	-1,25E+04	-1,54E+04	3,05E-01	1,28E-01	3,40E-02	2,09E+10
2,81E+03	-1,25E+04	-1,54E+04	3,04E-01	1,01E-01	1,01E-01	1,00E+09
2,81E+03	-1,24E+04	-1,53E+04	3,08E-01	1,12E-01	1,12E-01	1,00E+06
2,81E+03	-5,70E+03	-8,66E+03	5,95E-01	1,01E-01	1,08E-01	1,00E+04
2,81E+03	-5,39E+03	-6,01E+03	7,58E-01	1,03E-01	1,07E-01	5,00E+03
2,81E+03	-1,04E+02	-3,30E+03	1,07E+00	1,22E-01	1,03E-01	2,00E+03
2,81E+03	5,62E+03	5,96E+01	8,29E+00	1,42E+00	2,24E-01	1,00E+02
2,81E+03	5,80E+03	2,49E+02	5,33E+01	1,38E+01	1,78E+02	1,00E+01
2,81E+03	3,22E+03	2,59E+02	6,95E+01	2,62E+01	1,79E+02	5,00E+00
2,81E+03	3,22E+03	2,68E+02	8,57E+01	6,79E+01	1,79E+02	1,00E+00
2,81E+03	3,23E+03	2,70E+02	8,96E+01	8,77E+01	1,79E+02	1,00E-01

Moment (Nmm), Max Rotation (^{0}), Stiffness (N/mm)

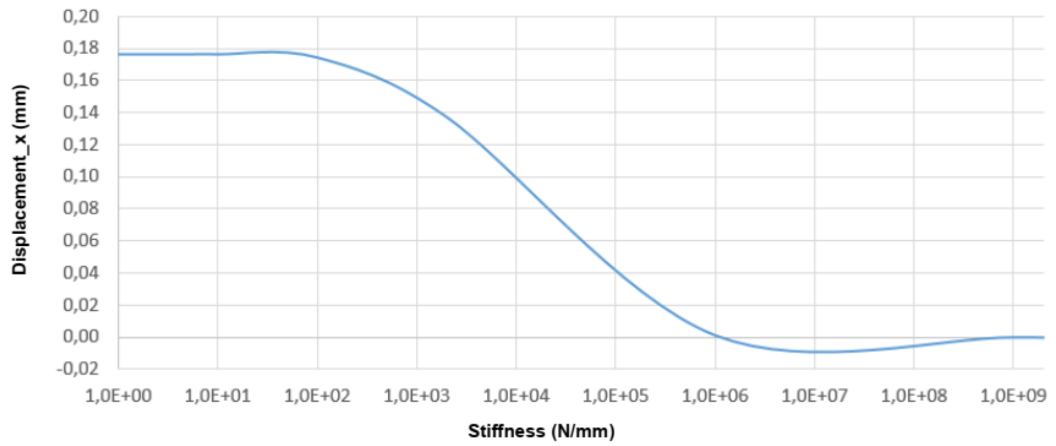
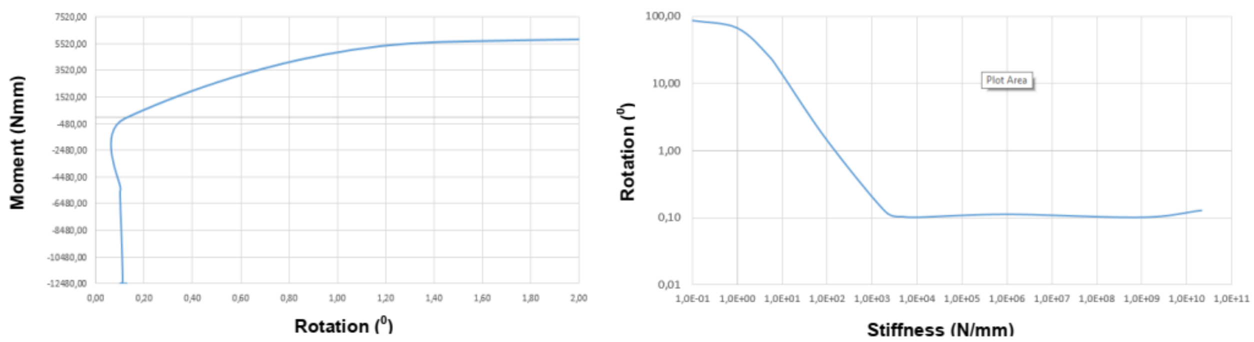


Figure 12. Displacement/stiffness graph obtained by linear static analysis of rack connection (x direction)



a) Moment/rotation graph (y-direction) b) Rotation/stiffness graph (y-direction)

Figure 13.Moment/rotation - rotation/stiffness graphs obtained by linear static analysis of rack connection

RESULTS

As a result, the mechanical behavior of structural systems for frame, scaffolding and rack were examined under determined loads and the following results were obtained;

1) *Mechanical behavior of the connections used in the frame structure under specified loads;*

As can be seen from Figure 7, connection elements can create the biggest displacement in configuration-6. In general, when looking at other configuration types, the stiffness of the system gets the lowest value compared to other designs (except for Configuration-5 Nod5). In addition, the load on the legs is distributed evenly. However, in this case, the moments carried by the system elements reach the maximum level. In this design, the load that the system carries is on the system elements rather than the connection elements. In this case, a risk arises that the cross sections will enlarge in order for the system to bear high moments. System strength should be controlled separately for optimum design.

Configuration-2 is the model in which the connection elements are most rigid and the deformation is in minimum. Making connections in constructions in this way both increases costs and causes sudden collapses under overload. The purpose of this study is to use semi-rigid connections that will allow the deformation of the system rather than such designs.

2) *Mechanical behavior of the connections used in the scaffolding structure under specified loads;*

When the displacement/stiffness graphs in Figure 9 are examined, we see that the system collapses by becoming kinetic below a certain stiffness value. It is seen that the stiffness value in the connections does not change as of a certain stiffness value. From this point of view, the connection stiffness should be selected not to be high enough to make the system too rigid, but on the other hand it should be chosen not to be low enough to make the system kinetic and to collapse. Maximum displacements in the system were observed in the X direction. Considering Figure 9-b, adding stiffness values over 1.0e+09 N/mm to the system has no effect on system stiffness. Therefore, in order to obtain an optimum design in terms of cost, this point should be paid attention and the strength of the structure and connections should be separately checked. In order to model the system with the semi-rigid approach, the stiffness value can be chosen as a value around 1.0e+08 according to the system strength results. The graphs obtained show that it is possible to obtain nonlinear results using the linear analysis method when appropriate stiffness values are selected for system connections. As a result, it is considered that the analyzes made using the semi-rigid method model the behavior of the structure in the elastic-plastic region as real as possible.

3) *Mechanical behavior of the connections used in the rack structure under specified loads;*

Although Figure 12 and Figure 13 show that the behavior of the system under selected constraints is quite rigid, the graphs obtained reveal the expected behavior of the system. Figure 12 shows that the system behavior does not change after the stiffness value of 1.0e+06 N/mm, after this level, a connection element that will make the system more rigid will only increase the cost. In order to design the structure in the semi-rigid region, it will be convenient to select the actual values of the connection stiffness around 1.0e+4 N/mm. The system starts to become kinetic after 1.0e+2 N/mm. This is manifested by the excessive increase in rotational values for values below 1.0e+2 N/mm in Figure 13-b graph. Figure 13-a cause the connection to be exposed to excessive torque values for connection stiffness values over 1.0e+4 N/mm. This is undesirable.

In this study, the way stiffness value of the fasteners affects the behavior of the system for the scaffolding and rack structures has been examined and a method that has to be followed has been created in the modeling of such structures with a low cross-sectional area.

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