Structural analysis for final design of International Thermonuclear Experimental Reactor sector sub - assembly tool

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Abstract

The Sector Sub-assembly Tool is a special tool for assembly of ITER Tokamak and is used to sub-assemble the 40°Tokamak sector which consists of vacuum vessel sector, vacuum vessel thermal shield sector and two toroidal field coils. The sector assembled in the assembly building is a basic and fundamental unit for the construction of the ITER Tokamak. The functions of the Sector Sub-assembly Tool are to support and handle heavy components which weigh up to 1200 t. The Sector Sub-assembly Tool is one of the most important tools to perform the assembly of ITER. To assess the design and structural integrity of the Sector Sub-assembly tool, the structural analyses have been performed under the load combinations according to load specifications. The results of the structural analyses show that the stresses of the Sector Sub-assembly Tool are below the allowable stress. This paper provides briefly the result of structural analysis for the Sector Sub-assembly Tool.

Keywords- **Seismic analysis FEA, ITER sector.**

I. Introduction

ITER Tokamak assembly is mainly composed of lower cryostat activities, sector sub-assembly, sector assembly, in-vessel activi-ties and ex-vessel activities [1]. The Sector Sub-assembly Tool, the Upending Tool, Sector Lifting Tool, Vacuum Vessel Support and Bracing Tools are required to implement sector sub-assembly pro-cedures. Sector sub-assembly is to integrate 40° Tokamak sector which consists of vacuum vessel sector (VV), vacuum vessel ther-mal shield sector (VVTS) and two toroidal field coils (TFC). The 40° sector assembled in the assembly building is a basic and funda-mental unit for the construction of the ITER Tokamak. Therefore, the Sector Sub-assembly Tool (SSAT) is one of the most important tools to complete the assembly of ITER Tokamak. The structural analyses have been performed including deadweight, payload and horizontal loads according to the load specification [2] and rele- vant EN standards [3,4] in order to assess the structural stress of the Sector Sub-assembly Tool. For the structural analysis, the main components are considered by the point mass element. In order to validate the use of point mass method, the comparative study has been performed. This paper provides briefly the results of the structural analyses for the SSAT.

II. Design description

The SSAT is composed of main structure, two rotating frames, and lower component supports including rail system and aligning units. Overall size of this tool is 16.7 m (L) × 16.5 m (W) × 22.6 m(H) and weight is about 820 t, respectively. The configuration of the SSAT is shown in Fig. 1. The main structure of the SSAT comprises three columns, two horizontal beams and support beam. The function of the main structure is to support the main components (VV, VVTS, TFCs) including the radial beam. Two rotating frames have an alignment function with the hydraulic pressure system to assemble the two TFCs and the VVTS segments [5]. In order to align the TFCs and VVTS segments in their final position, 6-DOF (three translation DOF: radial, toroidal, vertical direction, three rotational DOF: r, t, v direction) alignment system is required. Therefore, the rotating frame has three alignment units which are the upper align unit, the middle align unit and the lower align unit including the spherical bearings. The upper align unit has r align cylinder and t align cylinder. The middle align unit has v align cylinder. The lower align unit has vertical align cylinder and radial align cylinder. The roller units under the bottom of the rotating frames are installed with Hilman rollers and a hydraulic skidding system to move the frame from initial position to the final position in toroidal direction [6]. The VV including the radial beam is installed on the main structure. Then, VVTS inboard and outboard segments are assembled with temporary support by the rotating frames. Two TFCs are assembled by the rotating frames. Then, inter-coil structures are installed and the VV-VVTS-TFCs are braced by the bracing tools. After completion of sub-assembly, the sector is transferred to the TOKAMAK pit.

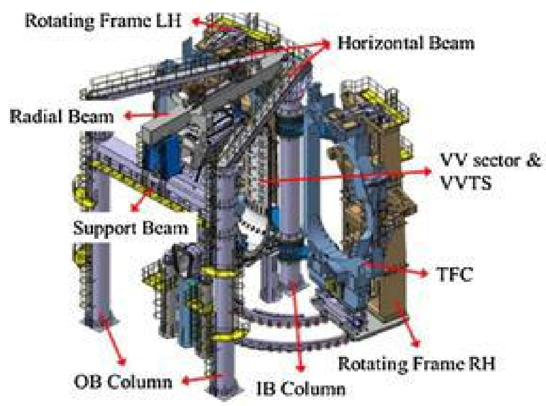

Fig.1: Configuration of the sector Sub-assembly Tool.

III. Finite element model

The structural analyses for SSAT are carried out using the commercial ANSYS code which is based on the Finite Element Method (FEM). Most of SSAT structures consist of thin plate. Thus, most of SSAT structures are modelled using the shell elements. All shell surfaces are offset to the middle surface of the geometry. For some parts such as Rail, Radial Beam IB Pin, VV vertical Rod and etc. that could not be generated the finite element (FE) model using shell element, the solid and the beam elements are used. And also, contact/target elements and joint elements are used in order to dis-tribute or transfer forces of displacements between unconnected parts. The mass element is used for the payload (VV, VVTS and TFCs) with their mass and rotational inertias. FE model of the SSAT is shown in Fig. 2.SM490 YB of KSD 3515 [7] is considered for the main structure and rotating frames. SCM440 of KSD 3867 [8] is applied to the pin, shaft in SSAT. The equivalent materials are S355 of EN 10025-2 and 42CrMo4 of EN 10083-3, respectively. The material properties used in this analysis are summarized in Table 1.

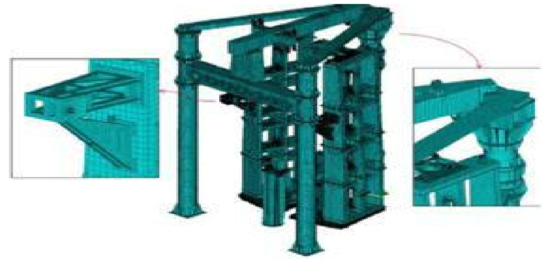

Fig.2 FE model of the sector Sub- assembly Tool.

Table 1: Material property for SSAT.

Material	Density [kg/m^3]	Elastic modulus [GPa]	Poisson's ratio	Yield strength [MPa]
SM490 YB	7850	206	0.3	355
SCM440	7850	206	0.3	500

Table 2: Load combinations for SSAT.

Part	Classification	Load Combinations		Allowable Stress
Main Structure	Steel Structure	LC1	DW + PL	0.91xF_y
		LC2	$PF_G \cdot DW + PF_{Q1} \cdot (DF_S) \cdot PL + PF_{Q2} \cdot HL_S$	
		LC3	DW + PL + SL-1	
Rotating Frame	Lifting Table	LC1	DW + PL	0.66xF_y
		LC2	$PF_G \cdot DW + DF_T \cdot PL + HL_T$	
	Steel Structure	LC3	DW + PL + SL-1	0.91xF_y

DW: Dead weight of SSAT.
PL: Payload (mass of VV: 450 t, VVTS: 30 t, TFCs: 2 × 311 t).
DF_S: Dynamic factor for steel structure, equal to 1.15 [3].
DF_T : Dynamic factor for lifting table, equal to 1.4 [4].
HL_S : Horizontal load for steel structure, 0.05 g [3].
HL_T : Horizontal load for lifting table, 0.1 g [4].
PF_G : Partial factor for dead weight, equal to 1.35 [3].
PF_{Q1},PF_{Q2}:Partial factor for variable load, equal to 1.35 [3].

IV. Analysis condition

A. Boundary condition

For the boundary condition of the main structure, the bottoms of three columns are constrained in all DOFs, since three columns are anchored on the assembly hall. For the rotating frames, the bot-tom surfaces of the rollers are fixed in the z direction, because the rotating frames are on the rail. And some clamps are constrained in all DOFs, since the clamps are bolted to the base plate in the final position.

B. Load condition

The classification of the main structure and the rotating frame is steel structure and lifting table, respectively, since the main structure and the rotating frame has different function. The reference standards for steel structure and rotating frame is EN 1991-3 and EN 1570-1, respectively. According to EN 1991-3, partial factor should be considered for dead weight, dynamic factor and hori-zontal load. In the EN 1570-1, dynamic factor and horizontal load is required only. However, partial factor for dead weight is considered in order to take into account the uncertainty of the dead weight. The required load combinations are summarized in Table 2. There are 4 sub-cases (+X, −X, +Y, −Y direction) to consider the horizontal load for LC2. The main structure is symmetric with respect to the XZ plane, −Y horizontal load is excluded. LC3 is including the seismic loads. The seismic loads acting on the SSAT and the components (VV, VVTS, TFCs) being handled are defined by means of Floor Response Spectra (FRS). The FRS is based on the envelope of the Seismes Majores de Securite (SMS) and PALEO spectra for the Cadarache site given in [9]. As the SSAT is a welded or bolted structure with friction connections, 3% damping is applicable for SL-1. The SL-1 FRS is shown in Fig. 3. For LC3, response spectrum analysis has been performed using the Square Root Sum of Square (SRSS) of modal combination.

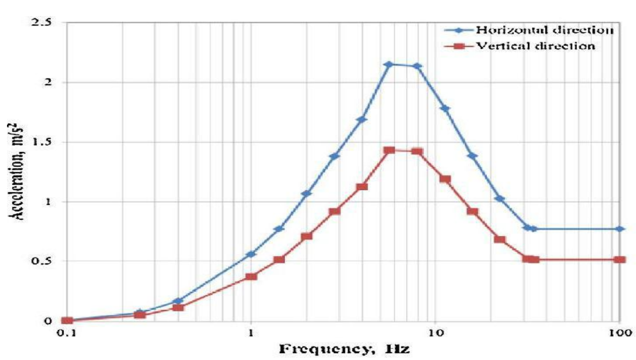

Fig .3: SL-1 Response spectrum of assembly hall.

V. Analysis results

A. Static analysis results

The static structural analyses have been performed for the main structure and the rotating frame under LC1 and LC2, respectively. The analysis results are summarized in Table 3. The allowable stress for the main structure is 0.91 times the yield strength of SM490 YB [2], and the value is 323 MPa. For the rotating frame, the stresses in any part shall not exceed 0.66 times the yield strength of SM490 YB [2,4]. Thus, the allowable stress for rotating frame is 234 MPa. Since the partial safety factor and dynamic factor is considered for LC2, the results show that LC2 is the most severe combination. The maximum stress of 269.6 MPa occurs at the VV temporary support cylinder for LC2 (+Y). And the stress margin is 20% for the main structure. For the rotating frame, the maximum stress is 202.9 MPa on the upper align unit under LC2 (-X). The stress margin is 15%. The equivalent stress distributions are shown for LC2 of the main structure and the rotating frame in Fig. 4.

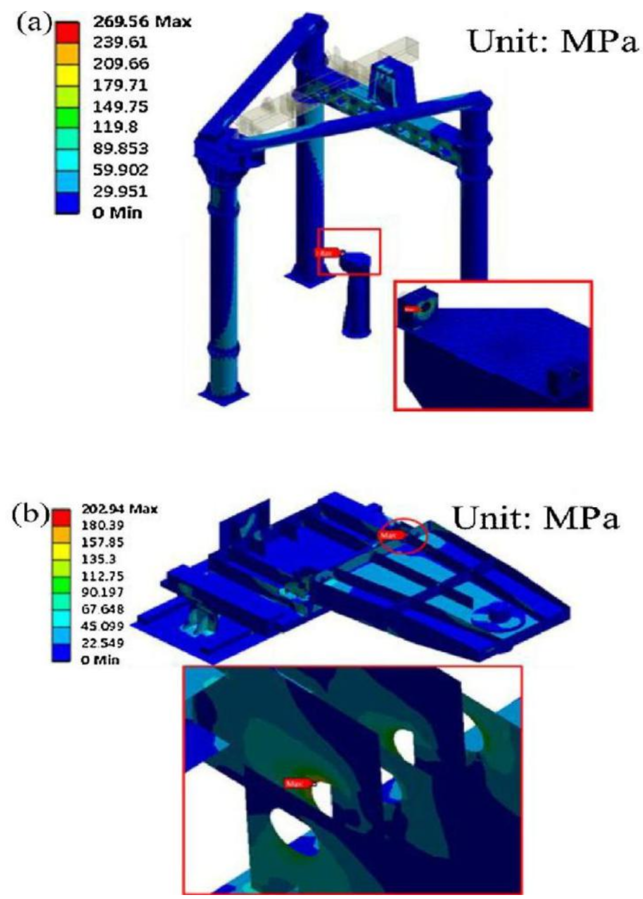

Fig. 4: Equivalent stress distribution for LC2.

(a) Equivalent stress distribution on the main structure.
(b) Equivalent stress distribution on the rotating frame.

Table 3: Analysis results on the SSAT.

Part	Load Combination	Max. Stress [MPa]	Allowable Stress [MPa]	Margin [%]
Main Structure	LC1	140.3	323.0	130
	LC2 (+X)	238.0	323.0	36
	LC2 (-X)	248.3	323.0	30
	LC2 (+Y)	269.6	323.0	20
	LC3	177.0	323.0	82
Rotating Frame	LC1	59.0	234.0	297
	LC2 (+X)	177.5	234.0	32
	LC2 (+Y)	200.2	234.0	17
	LC2 (-X)	202.9	234.0	15
	LC2 (-Y)	201.6	234.0	16
	LC3	247.6	323.0	30

B. Response spectrum analysis results

Modal analysis has been carried out in order to obtain natural frequency, Eigen modes and modal participation factor. The total effective masses of x, y and z direction are 97.3%, 96.7% and 92.4%, respectively. Then, response spectrum analysis has been performed in each direction using modal results. The results from different direction of excitation are combined using SRSS method. Then, the result of static analysis under dead weight is added into the results of spectrum analysis. The combined result is shown in Fig.

5. The maximum stress 247.7 MPa occurs at the lower align unit. And the stress margin is 30%.

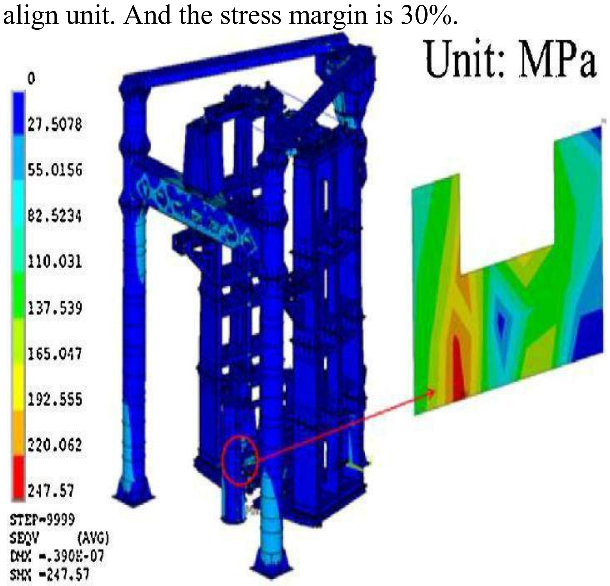

Fig.5: Equivalent stress distribution for LC3 (DW + SL1).

C. Validation of using point mass

For the static and spectrum analysis of SSAT, VV, and TFC struc-ture should be considered as a payload. When VV and TFC structures have an adequate stiffness, the structures could be considered as a rigid body. This assumption would not be big impact to the results of the static and spectrum analysis. In order to validate the use of point mass method, the modal and spectrum results were compared for point mass model and simplified model of VV and TFC which are created by using a shell and beam element with their equivalent stiffness. The first 30 modes were extracted for both models. The major modes of each direction are summarized in Table 4. For the first major mode, two models have similar frequency and effective mass. However, the difference is 20% for the second and third major mods of z direction. The reason of the difference could be the use of point mass for VV and TFC. To evaluate the influence of stress results due to the difference, the spectrum analysis was performed for both models. The results of spectrum analysis are summarized in Table 5. The stress results in x and y direction is similar for both models. The differences are 8% and 2% for the maximum equivalent stress. Forz direction, the stress of point mass model is 25% higher than sim-plified model. However, the combined stress for three directions is 143.0 MPa and 145.0 MPa for point mass and simplified model. Even the stress results in z direction have the difference of 25%, the difference of the combined stress results is only 2%. Because the stress level in z direction is lower than other direction (Fig. 6).

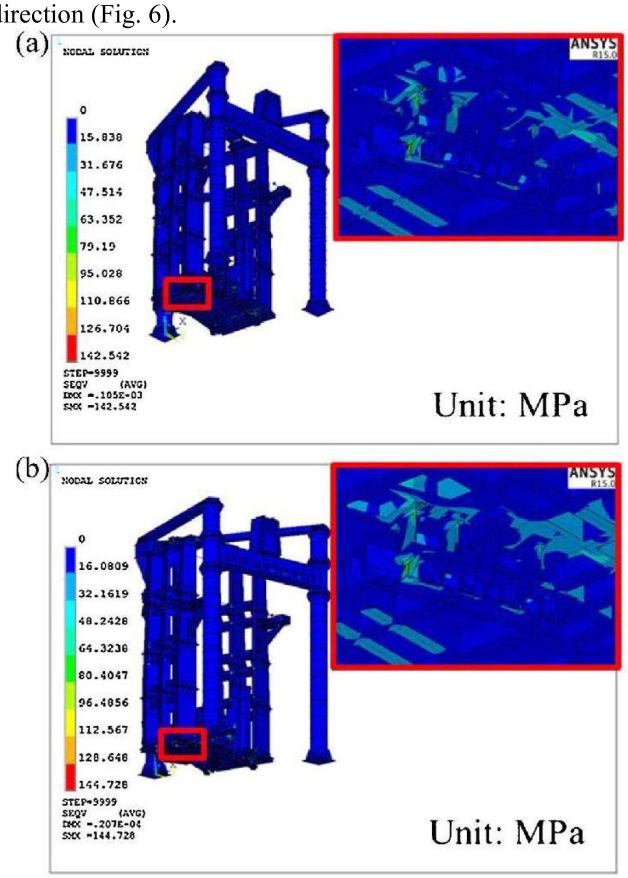

Fig. 6: Equivalent stress of SRSS combination.
(a) Equivalent stress for point mass model.
(b) Equivalent stress for simplified model.

Table 4: Summary of Modal Analysis.

Direction	Point mass model		Simplified model		Diff. [%]
	Freq. [Hz]	Eff. Mass Ratio [%]	Freq. [Hz]	Eff. Mass Ratio [%]	
X	2.52	46.1	2.34	45.7	7
	0.59	30.7	0.55	30.6	7
Y	1.54	36.7	1.52	36.7	2
	0.92	26.8	0.91	20.3	1
Z	5.04	27.8	4.73	26.8	3
	16.57	25.0	13.23	17.5	20
	16.55	13.0	13.24	7.7	20

Table 5: Summary of Response Spectrum Analysis.

Direction	Max. equivalent stress [MPa]		Difference [%]
	Point mass model	Simplified model	
X direction	111.1	102.2	8
Y direction	142.4	144.6	2
Z direction	33.8	25.3	25
SRSS	142.5	144.7	2

VI. Conclusion

The final design of the SSAT has been developed by ITER Korea. The conclusion of this study are given below. The structural anal-yses including seismic load have been performed for LC1, LC2 and LC3 to investigate the structural stress of the SSAT. The most severe combination is LC2 for SSAT. The maximum stress is 296.6 MPa and 202.9 MPa for the main structure and rotating frame, respectively. The maximum stress for SSAT is lower than allowable stress. The comparative study has been carried out to validate the use of the single point mass. The stress results in x and y direction is similar for both models. The differences are 8% and 2% for the maximum equivalent stress. For z direction, the stress of point mass model is 25% higher than simplified model. The stress level for z direction is very lower than the other direction. Therefore, the combined stress is well similar for both models. The result of the comparative study shows that there are no significant differences between point mass model and simplified model. The manufacturing of SSAT is almost completed. Factory acceptance test (F.A.T.) including load test will be carried out. In F.A.T., the displacement and the strain will be measured on the major part. Then, the results will be compared to the analysis results.

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