Degree Thesis, Åland University of Applied Sciences, Degree program in Mechanical Engineering

Methodology for Seismic Analysis

Electrically Operated Globe Valve

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Abstrakt

Syftet med vår avhandling är att definiera en omfattande metodik för seismisk stressanalys av en klotventil i samband med de nya riktlinjerna efter Fukushima-olyckan. Lastkombinationer utförs enligt ITER:s lastspecifikationsriktlinjer. Lasterna delas in i primärlaster, sekundär- och olyckslaster eller tillfälliga laster. Utrustningen kontrolleras för styrka och tryckintegritet inom stressgränser och acceptanskriterier.
För seismisk analys utförs en modal analys för att hitta ventilens naturliga frekvens och modform. Kritiska punkter beaktas för stresslinjärisering för att klassificera påfrestningar. Stressklassificeringen utförs för att uppfylla stressgräns kraven i ASME BPVC, Section III, Sub-section NC.

Nyckelord (sökord):

Jordbävning, Fusion, Kärnkraft, Kylsystem, Design, Analysmetodik

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Commissioned by:	International Thermonuclear Experimental Reactor (ITER), Peter Brenier

Abstract

The purpose of our thesis is to define a comprehensive seismic stress analysis methodology for a globe valve in context of the new guidelines after the Fukushima accident. Load combinations are performed as per ITER:s load specification guidelines. Loads are divided into primary loads, secondary- and accidental loads or occasional loads. Equipment is checked for strength and pressure integrity within stress limits and acceptance criteria.
For seismic analysis, a modal analysis is performed to find the valves natural frequency and mode shape. Critical locations are considered for stress linearization to classify stresses. The stress classification is performed to satisfy the stress limit requirements of ASME BPVC, Section III, Sub-section NC.

Keywords

Seismic, Fusion, Nuclear power, Cooling system, Design, Analysis methodology

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1. INTRODUCTION

1.1 Background

ITER is a huge energy project that started back in 1985. It's funded and managed by several countries, including the EU, India, Japan, China, Russia, South Korea, and the United States. They began building the ITER Tokamak complex in 2013, and the most recent official cost estimate stands at more than $22 billion so far. They plan to finish building it by 2025. The main goal of ITER is to create the world's largest tokamak, which is a device that uses magnets to produce energy from fusion. This could be a big source of clean energy for the future (ITER, 2024).

1.1.1 Fusion

Fusion powers the sun and stars. Within the intense heat and gravity at their cores, hydrogen nuclei collide and merge into heavier helium atoms, releasing vast amounts of energy. ITER will utilize two hydrogen isotopes, deuterium (D) and tritium (T), as fuel because the DT fusion reaction yields the highest energy output at relatively “low” temperatures.

Deuterium can be extracted from seawater in virtually unlimited quantities, but the available supply of tritium is limited. However, there is another source: tritium can be produced within the tokamak when neutrons escaping the plasma interact with lithium in the blanket. This concept of “breeding” tritium during the fusion reaction is crucial for the future needs of large-scale fusion power plants (ITER, 2024).

Three conditions must be fulfilled to achieve fusion:

- Very high temperature (~150,000,000 °C)
- Sufficient plasma particle density (to increase the likelihood that collisions occur)
- Sufficient confinement time (to hold the plasma, which tends to expand within a defined volume).

At extremely high temperatures, electrons are stripped from nuclei, transforming a gas into plasma, the fourth state of matter. Fusion plasmas create the conditions necessary for light elements to fuse and release energy. In a tokamak device, strong magnetic fields are employed to confine and control the plasma (ITER, 2024).

1.1.2 Tokamak

The tokamak is a full-scale experimental machine designed to harness fusion energy. Inside a tokamak, the energy generated from atomic fusion is absorbed as heat by the vessel walls. Like a conventional power plant, a fusion power plant will use this heat to produce steam, which then generates electricity through turbines and generators. Although ITER is an experimental power plant and won't produce electricity, its operation will enable ITER Members to test long-pulse operation and the necessary technologies at a reactor scale.

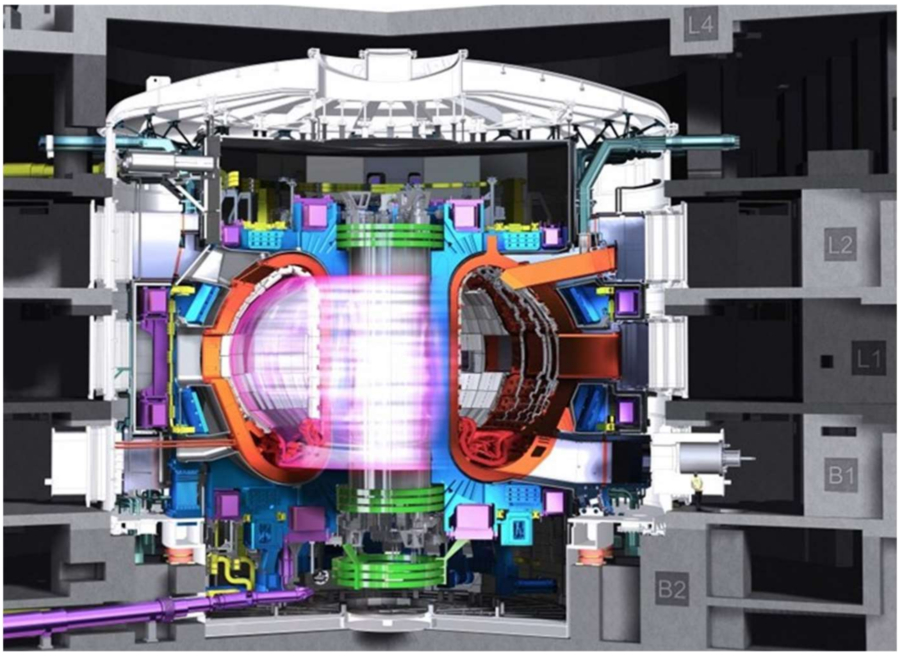

Figure 1: Illustration of the tokamak, which its heart, is its doughnut-shaped vacuum chamber.

To initiate the process, air and impurities are first removed from the vacuum chamber. Then, the magnet systems designed to confine and control the plasma are charged, and the gaseous fuel is introduced. When a powerful electrical current passes through the vessel, the gas breaks down, becomes ionized (electrons are stripped from the nuclei), and forms plasma. As the plasma particles become energized and collide, they heat up. Auxiliary heating methods further raise the plasma to fusion temperatures (150 - 300 million °C). At these temperatures, particles can overcome their natural electromagnetic repulsion upon collision, allowing them to fuse and release vast amounts of energy.

The ITER Tokamak will rely on three sources of auxiliary heating methods, neutral beam injection and two sources of high-frequency electromagnetic waves (ITER, 2024).

1.1.3 ITER:s goal

- **ITER is designed to achieve a ten-fold energy return (Q = 10), generating 500 MW of fusion power from 50 MW of input heating power.**
  While ITER won't convert this energy into electricity, it will pave the way for future full-scale machines capable of doing so.
- **Achieve a deuterium-tritium plasma in which the reaction is sustained through internal heating.**
  Fusion research is on the verge of exploring "burning plasma," where the heat from the fusion reaction is efficiently confined within the plasma, allowing the reaction to be sustained for extended periods. Scientists are confident that the plasmas in ITER will not only generate significantly more fusion energy but will also remain stable for longer durations.
- **Develop technologies and processes needed for future fusion power stations.**
  Including superconducting magnets, refine neutron shield/heat conversion technologies, diagnostics, cryogenics and remote handling (maintained by robots).
- **Verify tritium-breeding concepts.**
  One of the key missions for the later stages of ITER operation is to demonstrate the feasibility of producing tritium within the vacuum vessel. The global supply of tritium is insufficient to meet the demands of future power plants. ITER offers a unique opportunity to test mockups of breeding blankets, known as Test Blanket Modules (TBM), in a real fusion environment. These test blankets will explore viable techniques to ensure tritium breeding self-sufficiency.

1.2 Topic Selection

- Everything started when we had to choose a thesis topic for the research method course.
- We were interested in alternate energy solutions and ended up choosing the ITER project as our topic on that course.
- When it was time to choose our thesis, we decided to keep ITER as our topic.
  - We contacted Florian Haug and told him about our idea. He got interested and together we discussed how to contact ITER to see if they had any thesis project to offer us.
  - ITER contacted us with an offer and here we are today.

- One month after we accepted the thesis offered by ITER, we made a study visit to France to see the facility and meet our external adviser, Peter Brenier.

1.3 Purpose

Considering the accident at the Fukushima nuclear power plant in Japan, the European Union Council declared, "the safety of all EU nuclear plants should be reviewed on the basis of a comprehensive and transparent risk assessment ("stress tests") (European Commission, 2012). It was agreed that the safety assessment would assess how nuclear installations can withstand the consequences of various unexpected events. These can range from natural disasters to human error or technical failure and other accidental impacts, such as transport accidents.

The purpose of our thesis is to define the methodology that needs to be followed while performing a stress analysis (seismic) of a valve in the cooling water system inside the Tokamak Complex using the **ANSYS© software**. We also talk about the ITER organization, its mission and fusion energy. For the paragraph below, we used the report we prepared for ITER as our source, which is included in the appendices.

1.4 Layout and Geometry

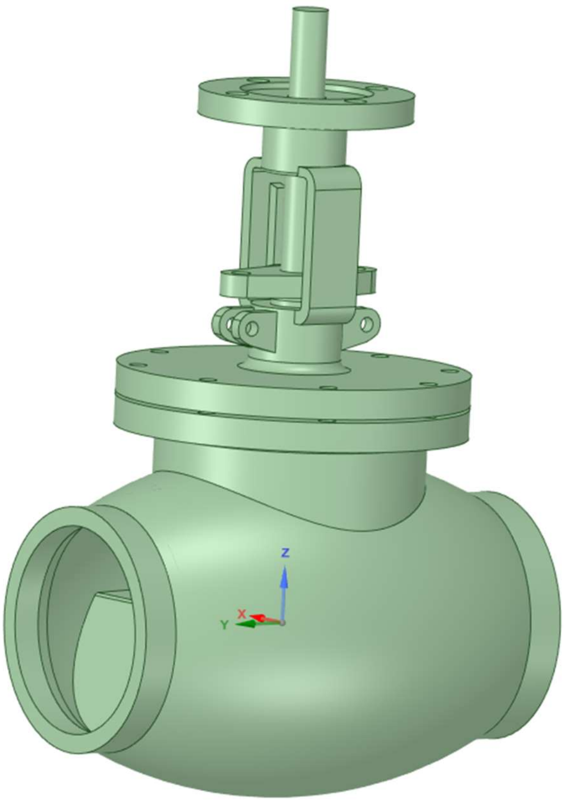

Figure 2: Illustration of the actual butt-welded valve to be used in the analysis.

1.4.1 Valve Specification

Tabell 1: Specifications of the Valve used in the analysis.

Valve type	Electrically operated globe valve
Nominal diameter	DN200
Design pressure	2.00 MPa (2.30 MPa)*
Design temperature	50 °C (70 °C)*
Body material	ASTM A 216
Extended structure type	Major extended structure **

Note:

* In the actual calculation and analysis, the design pressure and design temperature are respectively taken as 2.30 MPa and 70 °C. The purpose of this is to facilitate more valve coverage, see our ITER report for more details

** From ASME NC 3521 C: Where valves are provided with operators having extended structures and these structures are essential to maintaining pressure integrity, an analysis, when required by the Design Specification, shall be performed based on static forces resulting from equivalent earthquake accelerations acting at the centers of gravity of the extended masses.

1.5 Cooling Water System (CWS)

The ITER Cooling Water System consists of several sub-systems. The valve to be qualified in this methodology report is located in the sub-system called Chilled Water System (CHWS).

The Chilled Water System main functions are:

- Provides separate and redundant water cooling to Safety Important Components (SIC) in CHWS-H1.
- Provides cooling water to non-Safety Important Components (non-SIC) in CHWS-H2
- Rejects heat directly to the atmosphere.

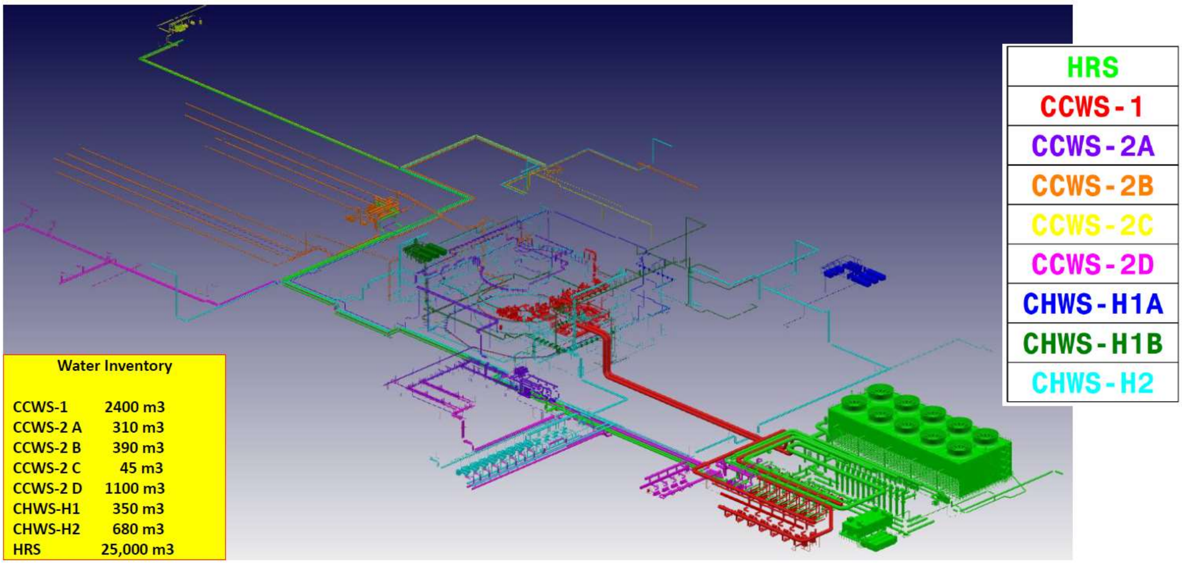

Figure 3: The relevant system for our thesis is the Chilled Water System H1-A (blue one) located on the right side of the tokamak.

1.6 Definitions

Tabell 2

Acronym	*Definition*
ASME	American Society of Mechanical Engineers
B-B	Body to Bonnet
BPVC	Boiler and Pressure Vessel Code
CCWS	Component Cooling Water System
CHWS	Chilled Water System
CoG	Centre of Gravity
D	Deuterium
g	Gravitational acceleration
HRS	Heat Rejection System
ITER	International Thermonuclear Experimental Reactor
SDOF	Single Degree of Freedom
SIC	Safety Important Components
SSC	Systems, Structure and Components
T	Tritium
TBM	Test Blanket Modules
ZPA	Zero Period Acceleration

2. METHOD

The method we use to qualify the valve can be seen in this Workflow chart below. In theory, we have a yes/no alternative based on the first natural frequency being above/below 33 Hz but in practice we know the valve will not be below since it is rigid.

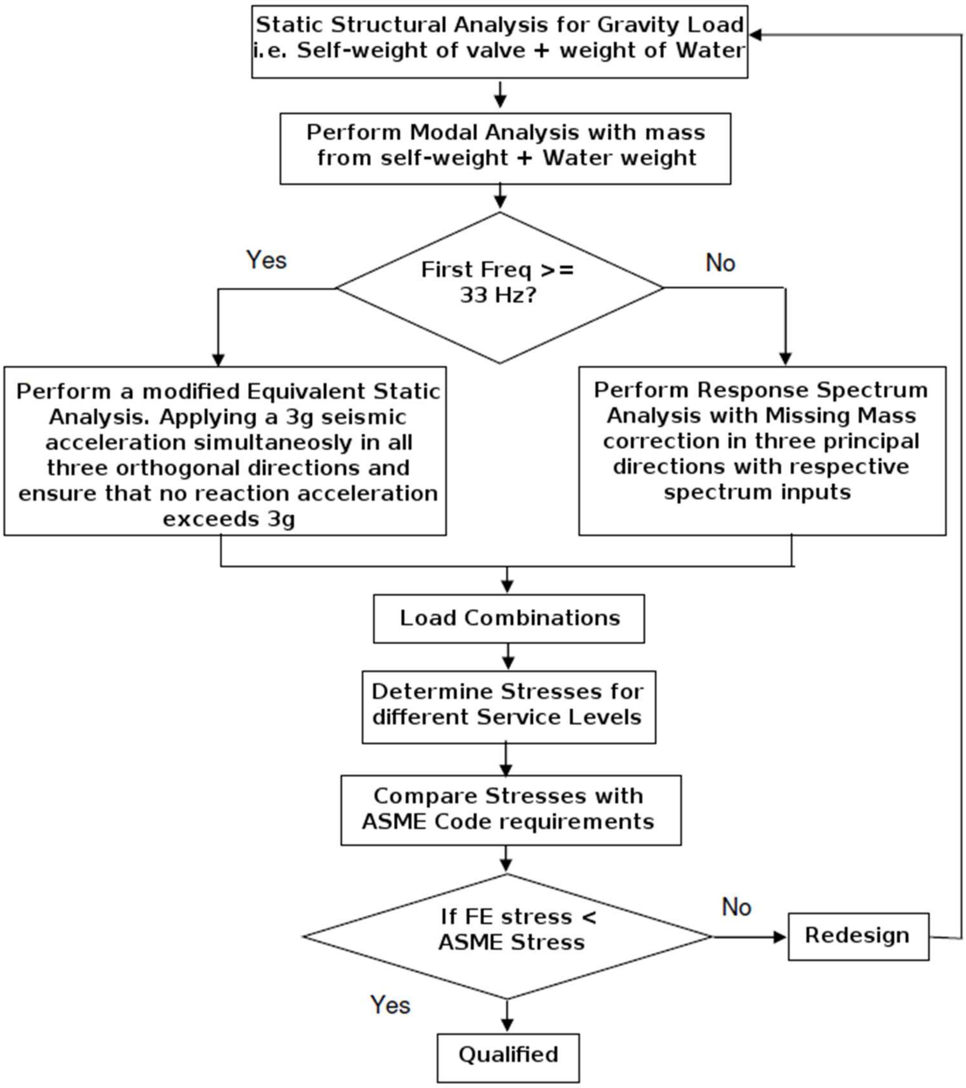

Figure 4: Workflow chart.

3. THEORY

3.1 Modal Analysis

Modal analysis is an important tool for understanding the vibration characteristics of mechanical structures. It converts the vibration signals of excitation and responses measured on a complex structure that is difficult to perceive (Zhao J, 2017).

Modal analysis extracts natural frequencies and shapes for the modes of vibration of the system. If the first natural frequency is equal to or above the cut-off frequency that is 33 Hz (ZPA) the system is considered rigid. Modes of vibration are calculated by solving the equation of motion for the system without external forces and damping:

$$[M]\{\ddot{X}\} + [K]\{X\} = 0$$

Here:

- [M] is the mass matrix consisting of all the lumped masses for every degree of freedom at each node of the system.
- [K] is the stiffness matrix.
- $\{\ddot{X}\}$ is the acceleration vector consisting of all accelerations and rotations that correspond to all degrees of freedom of the system.
- {X} is the displacement vector consisting of all displacements and rotations that correspond to all degrees of freedom of the system.

Natural frequency: Also known as, eigenfrequency is the frequency at which a system oscillates when not subjected to a continuous or repeated external force.

Mode shapes: A mode shape is the deformation that the structure would show when vibrating at its own natural frequency.

33 Hz: Is a standard value in the seismic industry for a structure to be considered rigid.

ZPA: Is the acceleration value corresponding to the cut-off frequency (33 Hz), or also called rigid frequency.

3.1.1 Method 1: Equivalent Static Analysis

This method is performed by static analysis. Force applied in equivalent static analysis is determined by considering the factor 1.5 times the acceleration value corresponding to 33 Hz

(ZPA) given in the enveloped response spectrum in all three orthogonal directions. These acceleration values are applied as gravity load in all three directions (x, y and z).

To obtain the ZPA as a gravitational acceleration the ZPA values are divided by 9.81 m/s^2 and then multiplied by the amplification factor of 1.5. The amplification factor is used to take into account that the SSC (Systems, Structures and Components) does not behave as a SDOF* (Single Degree of Freedom) system.

* In an SDOF system only one coordinate is needed to fully describe its configuration.

Note: The reason why we did not choose this method is because the Modified Equivalent Static Analysis is more cost-effective and less time consuming.

3.1.1.1 Method 2: Modified Equivalent Static Analysis (chosen method)

Since the system is considered rigid the first natural frequency will be above 33 Hz. We can therefore use a "Modified Equivalent Static Analysis" method for our analysis since it is a cost-effective approach and standard practice in the seismic industry. By consulting with ITER on previous projects we were able to estimate a reasonable seismic acceleration value for this analysis.

- With this approach, a seismic acceleration corresponding to 3 g is simultaneously applied in all three orthogonal directions.
    - This is how we obtain the Seismic Load.

The advantages with this approach:

- Cost-effective.
- Less time-consuming.

The disadvantage with this approach:

- Requires engineering experience from similar projects to estimate a reasonable seismic acceleration value to be applied in the analysis.

3.1.2 Method 3: Response Spectrum Analysis (Dynamic)

In the response spectrum method, the response (displacement, stress, etc.) obtained in each mode is the maximum. However, the maximum response will not all occur simultaneously. Absolute summation of response is highly conservative. There are several methods to reduce conservatism. Two of them are the Square Root of the Sum of the Squares (SRSS) and the Complete Quadratic Combination (CQC). We will not cover them here as they are quite complex and not relevant in our analysis case since our system is considered rigid, but we have covered the theory behind them in our full report.

Note: The response spectrum method is only used when the structure's first natural frequency (eigenfrequency) is below the cut-off frequency (= 33 Hz), meaning the structure is not rigid. A modal analysis is pre-required to determent the first eigenfrequency.

3.2 Loading Conditions

Tabell 3: The loads that will be considered in the FE analysis.

Load items	***Load value***	***Remarks***
Design pressure	$1.5 \times 2.3\, MPa = 3.45\, MPa$	Conservatively, the pressure value is 1.5 times of design pressure under the accident condition to compensate for loads during accident.
Temperature	-----	Temperature is only used to determine allowable stress.
Dead weight	Acceleration value 1 g = 9806.6 mm/s^2	Gravity acceleration.
Seismic load (SSE)	3 g acceleration $3 \times 9806.6 = 29419.8\, mm/s^2$ Composite equivalent seismic load $\sqrt{(3\,g)^2 + (3\,g)^2 + (3\,g)^2} = 50956.6\, mm/s^2$	Conservatively, 3g seismic acceleration simultaneously applied in three orthogonal directions (hand calculated).
Piping load	$M = F_b \times S'_y = 35472517\, Nmm$	Maximum moment before the pipe breaks (hand calculated).
Bolt pre-tension Load	12666 N Applied at each B-B bolts	Preload is the tension created in a fastener when it is tightened (hand calculated).
	9150 N Applied at each gland flange bolts	

3.2.1 Loading and Boundary Conditions

- **Figure 5**: Shows a model with the boundary conditions of all single load cases that is considered (since the bolt pre-tension load is considered separately it is not listed).
- **Note:** For the boundary condition of single loads (Design pressure, Dead weight, Seismic load) the valve will be fixed on both sides.
  - As for the **boundary condition of Piping Load** only one side will be fixed and on the other side the maximum moment before the pipe breaks will be applied.
    - Having two different boundary conditions does not matter because what ANSYS does is calculate the displacement. We do not need to

analyse the displacement that is near the support where the new boundary condition will affect that displacement the most. We only analyse/look at displacement further into the object's body, where the differences in displacement due to different boundary conditions will be close to zero. We can thus have different boundary conditions and achieve good results.

- **Figure 6:** Shows a model with the boundary conditions of combined loads.

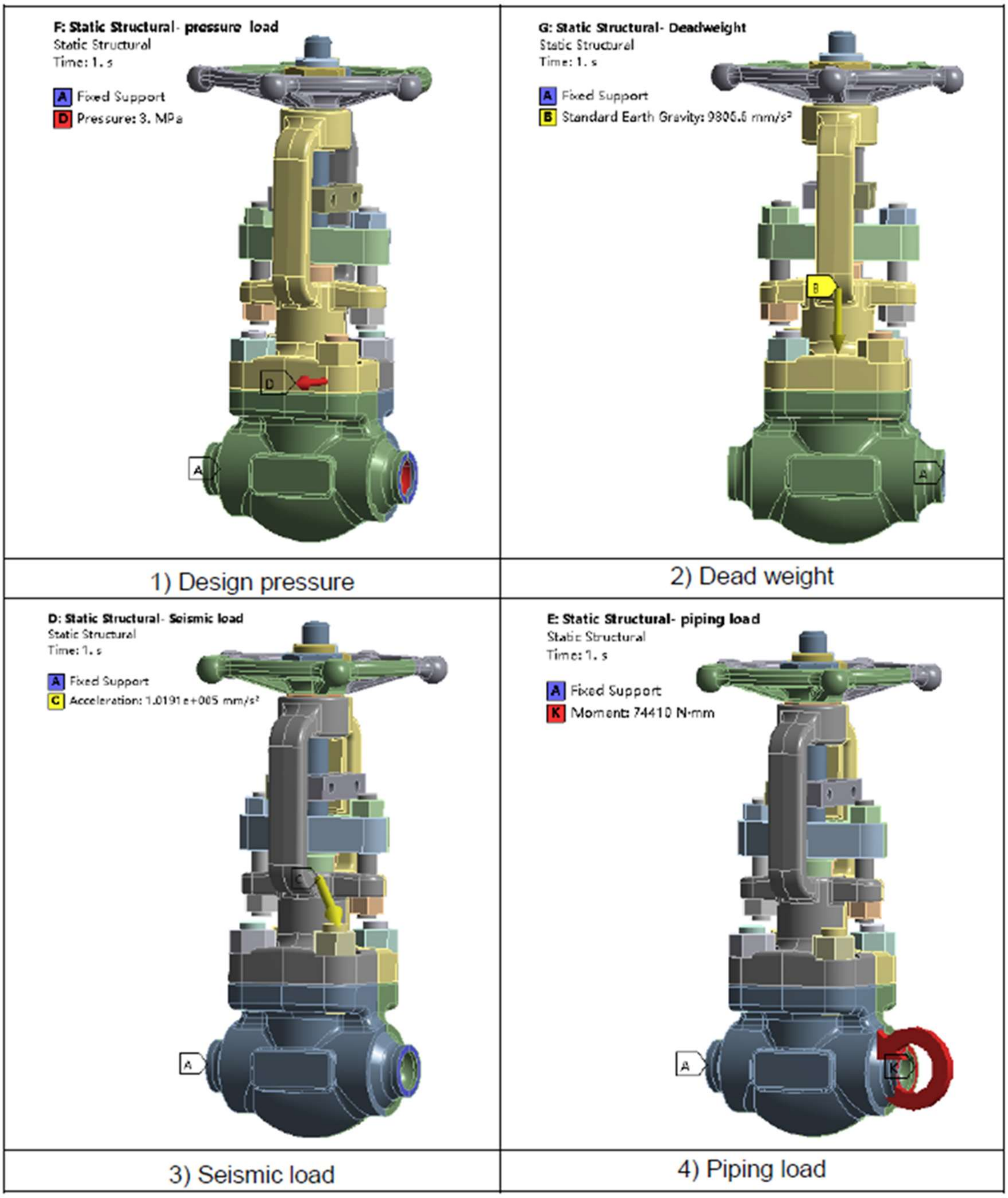

Figure 5: The valve in this figure is only to illustrate how to apply the boundary conditions and single loads. It is not the actual valve used in our thesis report.

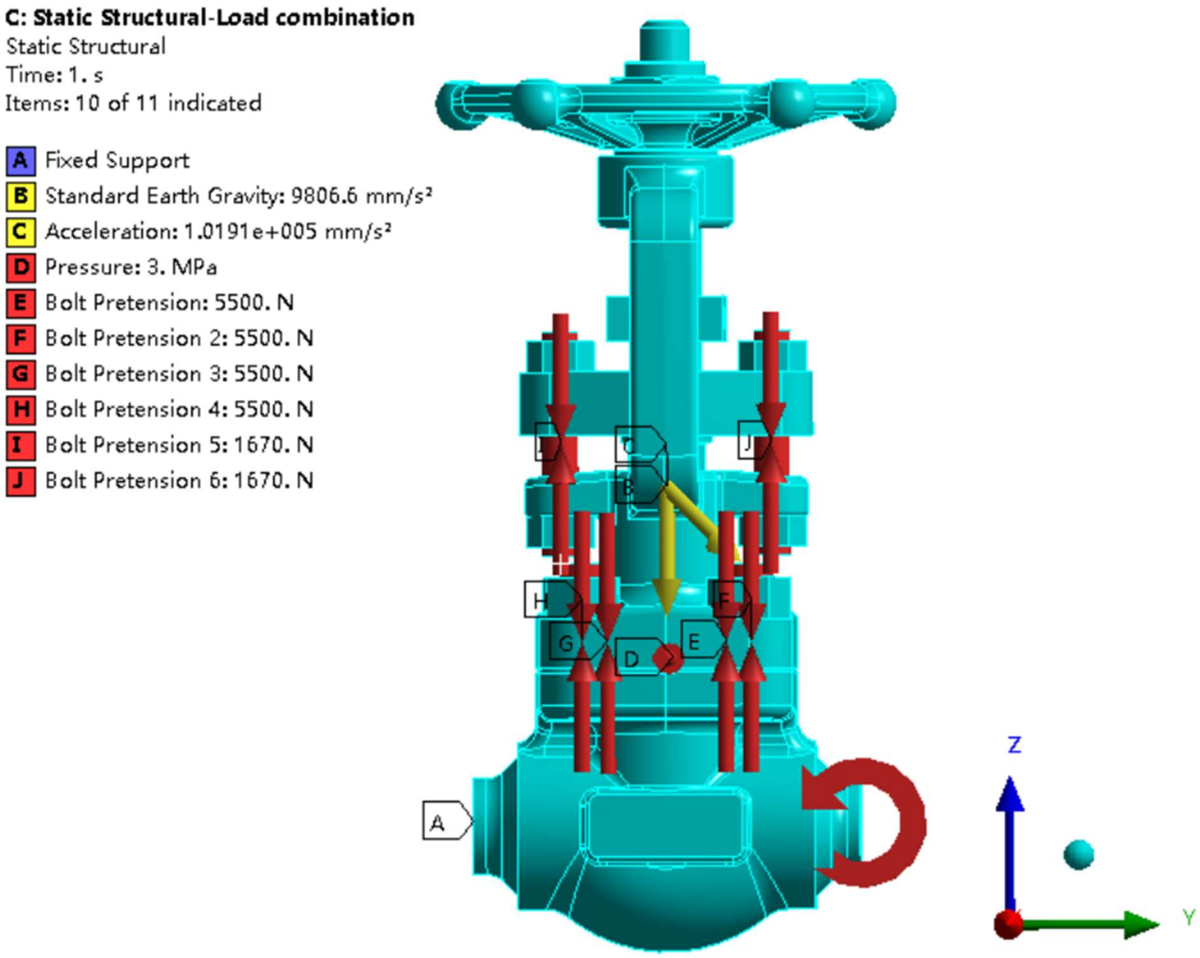

Figure 6: The valve in this figure is only to illustrate how to apply the boundary condition and combined loads. It is not the actual valve used in our thesis report.

3.3 Acceptance Criteria

The ASME code determines the minimum requirements the system has to withstand. ITER has however set a higher requirement upon themselves to ensure safety operations and therefore we will qualify the system for Service Level A and Service Level B.

- **Service Level A** – is equal to normal functionality in the system. The component should maintain specified service function within specified operational limit. No special inspection will be required other than routine maintenance and minor adjustments.
- **Service Level B** – is equal to upset functionality in the system. The component must withstand these loadings without significant damage requiring special inspection or repair.

Tabell 4: Acceptance criteria for elastic analysis.

Service limit	*Stress limits*	*Reference*
Service Level A	$\sigma_m \leq S$ $(\sigma_m \; or \; \sigma_L) + \sigma_b \leq 1.5S$	Table NC-3521-1 ASME Sec III subsection NC-2010
Service Level B	$\sigma_m \leq 1.1S$ $(\sigma_m \; or \; \sigma_L) + \sigma_b \leq 1.65S$	

Where:

- $\boldsymbol{\sigma_m}$ = General membrane stress. This stress is equal to the average stress across the solid section under consideration. It excludes discontinuities and concentrations and is produced only by pressure and other mechanical loads.
- $\boldsymbol{\sigma_L}$ = Local membrane stress. This stress is the same as σ_m, except that it includes the effect of discontinuities.
- $\boldsymbol{\sigma_B}$ = Bending stress. This stress is equal to the linear varying portion of the stress across the solid section under consideration. It excludes discontinuities and concentrations and is produced only by pressure and other mechanical loads.
- ***S*** = Allowable stress values as per Table 1A of ASME, section II, part D (Metric).

Tabell 5: Operability is required for active components, such as valves and actuators whose operation must be guaranteed to operate during and after the accident.

Requirement	*Service level*	*HCC affected*
Operability	A or B	Valves are to be able to operate during and after the accident

4. CONCLUSION AND DISCUSSION

- The subject was entirely new to us, and we had to learn all the necessary steps simultaneously (seismic analysis, qualification process, Ansys software, etc.) while writing the thesis.
- Our methodology still needs to be verified by Finite Element Analysis but that is outside the scope of this thesis.
- **Some obstacles we encountered:**

    - One challenging part was to work from distance as our external supervisor is in France. We communicated through Skype meetings once a month but as it is an important skill to have these days it was good to experience it.
    - We wasted a lot of time converting and trying to fix the errors on the drawing model we got from ITER since it was not compatible with ANSYS.
        - Eventually we made a new valve drawing ourselves from scratch in which was a timeline setback for the project.
    - Covid-19 did not make things easier.
- Final words: We would like to thank our supervisor Florian Haug, our adviser Peter Brenier at ITER and our school for making this project possible. It has been both challenging and educational, but we are happy with the experience we have gathered during this period.

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