Philosophy of stress-strain measurement for Proto-type Cryo-line of ITER

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Abstract. Large and complicated network of cryo-lines are required for the ITER cryogenic system, connecting cryo-plant, cryo-distribution system and applications. Fixed support, sliding support and vacuum barrier are the integral part of the design of the cryo-lines. These supports, apart from the purpose of supporting the dead weight of internal process pipes, take care of different forces generated due to the thrust, spring and the thermal load. Therefore, stresses are generated on them. In order to have a measurement of the stress, experiments are done with strain gages mounted on these components. For the proto-type cryo-line of ITER, stress analysis has been carried out and the contours of stress on these components are available. The measurement with strain gages will be done to validate the design as well as to get the idea of the absolute values of the stresses expected to generate. The temperature zones will be in the range of 4.5 K to 80 K. Therefore, special strain gage and its measurement have been planned for this purpose. The paper will discuss mounting process of the strain gages, the basis of deciding the location of gages, measurement procedure with error compensation and correction as well as data acquisition techniques.

1. Introduction
Complete network of cryo-line and manifold of the ITER cryogenic system is a part of in-kind supply for India. The design of the torus and cryostat cryo-line [1], out of the entire network is already carried out. The validation of the overall design concept, fabrication and assembly methodology, proto-type test [2] for such cryo-line is envisaged. During design work, mechanical stability and integrity are considered as the most important facet for the purpose of higher operational availability for longer periods. To authenticate this fact, static stress analysis is required. Stress analysis is carried out with commercially available software like ANSYS© and CAESER II© as per ASME B31.3. These analyses have to be supported by experimental confirmation. In proto-type cryo-line test, stress measurements at critical locations are mandatory for ensuring reliable design.

2. Stress measurement
Stresses at the location of interest can be assessed by measuring strain at these locations. For proto-type cryo-line [2] major stresses are evaluated to arise at the critical locations of internal process pipes like fixed support, sliding support, vacuum barrier and standard junctions. On the other hand, minor stresses are developed at internal process pipe, thermal shield. Measurement of stresses is dependent

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on the material of construction and operating conditions, which are described at table 1 along with its strain values. In this, operating temperature range is most important factor considering strain measurement point of view. Static stress is mainly considered as operating conditions and modes follow the same and dynamic stress contribution is negligible. Only possible dynamic stress occurrence is foreseen during seismic events. Many cases, principle stress axis is not possible to foreseen during software based analysis. In this case, validating experimental analysis is the solution.

Table 1. Stress-Strain on materials and operating temperature ranges.

| Material | Range of Stress (MPa) | Strain (μm/m) | Temperature of Material (K) |
|----------|-----------------------|---------------|-----------------------------|
| SS304L   | 0 – 300               | 0 – 2000      | 4.5 - 300                   |
| GFRP-G10/11 CR | 0 – 160              | 0 - 4500      | 4.5 - 300                   |
| Aluminum | 0 – 280               | 0 - 4000      | 70 - 300                    |

3. Strain gauge

Strain gauge is to be used for the measurement of strain directly and stress indirectly at the location of interest. foil type strain gauge is selected over semiconductor gage [3] because of its larger strain measurement range and stable as well as linear response at the wide range of temperature operation, even if foil type gage has lower sensitivity. Nickel-chromium alloy, which has a trade name of Karma alloy, is used for the foil with carrier backing of glass-fiber-reinforced epoxy phenolic resin. Foil resistance is selected as $1000\Omega$ for relative higher sensitivity than that of $120\Omega$ or $350\Omega$ foils. Foil having uni-axial and tri-axial configuration are employed for known as well as unknown stress axis having an axial sensitivity or gage factor of the order of 2.1 at room temperature. Figure 1, 2 and 3 show uni-axial and tri-axial gages for the measurement of known and unknown stress axes respectively. Two types of tri-axial gages are used and they are rectangular ($0^\circ$-45$^\circ$-90$^\circ$) rosette and delta ($0^\circ$-60$^\circ$-120$^\circ$) rosette.

4. Mounting of strain gauge

Mounting of strain gage is the most imperative and vital part of strain measurement, as otherwise, this could lead to a completely wrong result of strain. Mounting process is broadly categories in four segments, as (i) surface preparation, (ii) gage adhesion, (iii) gage termination and (iv) protective coating application. Surface preparation is then carried out in four following sequences. Mounting surface is degreased with the application of isopropyl alcohol. Degreasing is executed with uncontaminated solvent with ‘one-way’ wiping action. Surface is then abraded in dry condition with 220- or 320-grit silicon-carbide paper to remove any surface solid contamination or oxide. 320- or 400-grit is used for final abrading. Wet final abrading is also performed with conditioner with ‘one-way’ wiping. After abrading conditioner is applied and scrubbed with cotton-tipped applicators. After conditioning, gage location is marked on the surface, which is required for both the uni-axial and tri-
axial gage mounting. The final step in surface preparation is to neutralize the surface condition back to an optimum alkalinity in the range of 7.0 to 7.5 pH, which is suitable for gage adhesive systems.

Gage is mounted with adhesive. Hot curing of adhesive is performed with pressurization. Clamps along with temperature control heating tapes are employed for this purpose. Lead wire connection is carried out and residual contamination is removed by rosin solvent or toluene. At the end, protecting coating is applied to protect the gage from moisture and mechanical damage.

5. Strain measurement scheme
Because of strain, foil resistivity changes due to piezoresistive effect. This change in resistance is detected using Wheatstone bridge, with a configuration of quarter and half bridge. This is deflection type and voltage sensitive bridge. Figure 4 shows the quarter bridge configuration with gage, which is connected to the tensile arm. Standard resistance \( R_2 \) and \( R_4 \) are connected at compressive arms and \( R_3 \) is connected at other tensile arm. \( R_p \) and \( R_s \) resistors are used for zero or offset adjustment and sensitivity tuning. Lead resistance is distributed in tensile and compressive arm to cancel each other for same type of leads.

![Wheatstone bridge with gage in quarter bridge configuration.](image)

5. Errors
As strain measurement is done at low temperature application, several errors are required to be handled.

5.1. Error due to low temperature application and magneto-resistive effect
Due to cooling down, compressive stress is generated on the test material and corresponding strain with temperature is shown in figure 5. It shows strain values as -2535 µm/m, -3000.4 µm/m and -4154.5 µm/m for GFRP-10 (wrap direction), SS304L and aluminum respectively at 4.5 K. Because of the difference in thermal expansion co-efficient between test material and foil grid, temperature induced apparent strain is produced at gage. Apart from this, due to temperature, resistivity of foil grid is also altered causing more apparent strain reading.

To compensate this temperature induced error, a dummy gage, which is as same as active gage, is mounted at an elevated structure as shown in figure 6. This will have same temperature and same temperature induced strain as active gage. Dummy gage is then connected at the ratio arm of Wheatstone bridge as shown in figure 7, which is for known stress axis. Same lead resistance at both the gages will cancel each other their contribution at output and shows zero output voltage due to only temperature induced strain. For unknown stress axis, one dummy gage is connected at the ratio arm of bridge for a set of three active gages in a configuration as shown in figure 8. Selector switch \( S_1 \) is used to scan all three active gages \( (R_{g1}, R_{g2} \text{ and } R_{g3}) \) sequentially. Here each gage is coupled with \( 2R_L \) lead resistance and dummy gage is also coupled with \( 2R_1 \) to cancel their contributions.
5.2. Gage factor

Gage factor or axial sensitivity is the ratio of relative change in foil resistance to the applied axial strain at constant temperature. This shows following errors during strain measurements and their correction techniques are discussed.

5.2.1. Gage factor variation due to temperature. Gage factor variation of the order of ±0.9% to ±1.8% per 100 K is observed. Because of piezoresistive effect of foil, foil resistance changes and gage factor is also affected with change in temperature. To know exact temperature of test material, temperature sensor is also mounted in the vicinity of active gage. This error is nullified by multiplying the bridge output with a correction factor $K_1$ as in equation (1).

$$K_1 = \frac{G_{f,g}}{G_{f,T}}$$  (1)
Where, $G_{fg}$ is gage factor of foil at room temperature and $G_{fT}$ is the gage factor of foil at temperature $T$.

5.2.2. Difference between gage and instrument gage factor. It may be found out that gage factor of foil and measuring instrument is not same and 33.3% to 37.5% maximum variation of instrument gage factor over foil gage factor is observed depending upon gage geometry. This is corrected by multiplying the output of instrument with a correction factor $K_2$ as in equation (2).

$$K_2 = \frac{G_{fi}}{G_{fg}}$$

Where, $G_{fi}$ is the gage factor of the instrument and $G_{fg}$ is gage factor of foil at room temperature.

5.2.3. Transverse sensitivity. Gages are not completely insensitive to transverse strain. Strain at the end loops and at the width of the foil grid-lines are the main cause of transverse strain. This error becomes maximum when principle stress axis is perpendicular to the gage axis. This effect is mostly observed in tri-axial gages. This error is corrected at the data acquisition section using separate sub-routines for each tri-axial configuration.

5.3. Bridge resistance tolerance error and lead-wires
Standard resistances on bridges have finite tolerances. Again, mismatch in lead-wire resistance between gage and instrument is a practical difficulty. These two effects cause offset strain error. This can be compensated by tuning $R_z$ in figure 4, 7 and 8 after gage installation with lead wires.

5.4. Grid temperature
In case of test material at 4.5 K, foil grid temperature is dependent on two factors. One is joule heating because of bridge excitation. This effect is more significant in case of GFRP-10 as test material, as it has lower thermal conductivity, which causes lower heat dissipation and higher grid temperature. Other one is heat conduction along the lead wires to foil grid. First one is corrected by using dummy gage and optimizing bridge excitation, whereas second one is compensated by sufficient thermal anchoring of gage wire at the cold 4.5 K surface.

5.5. Young’s Modulus
Stress is finally calculated from the measured, corrected strain. Variation of Young’s modulus of test material is used for exact stress evaluation.

6. Shunt calibration
After gage is installed calibration [5], shunt calibration is a recommended practice. Shunt calibration is carried out by incorporating a high value shunt resistor across the active gage. Figure 9 shows gage calibration for all three foil grid resistances considering gage factor 2.1 at room temperature. This is simulating compressive strain.

7. Data acquisition scheme
Data acquisition is carried out using programmable logic controller (PLC) and supervisory control and data acquisition (SCADA) system in combination. All the error correction algorithms are carried out by PLC program using separate subroutines for each correction. Figure 10 shows complete scheme of strain measurement system.
8. Conclusion
The paper presents the methodology of stress – strain measurements which needs to be carried out for prototype cryolines of ITER. Both uni-axial as well as tri-axial stain gauges have been planned for the above measurements. Detailed procedure for measurements along with the errors which need to be taken into account have been outlined. There are certain other errors with this kind of strain gage measurements like manufacturing mismatch of backing material of active and dummy gage, misalignment of gages during mounting. Contribution of these kinds of errors is negligible. Hence, they are not considered for correction or compensation. During proto-type cryo-line test, various operating conditions are foreseen. Stresses at all the locations will be continuously monitored and interlocked with the operating mechanism to protect the system from failures.

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