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Evaluation of Ultimate Load Bearing Capacity of the Primary Containment of A Typical 540MWe Indian PHWR

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ABSTRACT

This paper presents the analysis of the Inner Containment Structure (ICS) of a typical 540 MWe Indian PHWR for the purpose of evaluating its ultimate load bearing capacity (ULBC) under beyond postulated design basis accident (DBA) scenario. The methodology adopted for the non-linear analysis of the prestressed concrete ICS including the various issues, viz. behaviour of concrete under compression and tension, tension stiffening, cracked shear modulus etc. have also been discussed in this paper. The effect of accident temperature on ULBC has been studied and discussed in this paper. This paper also discusses about the study carried out for mesh sensitivity of the finite element (FE) discretisation on ULBC of ICS in the non-linear range. Based on the detailed analysis, the factor of safety of the ICS under beyond postulated DBA scenario has been evaluated.

INTRODUCTION

The typical Indian PHWRs of 540MWe series are having a double containment system. The ICS is prestressed concrete and the outer containment structure (OCS) is reinforced concrete. The ICS is a cylindrical structure of 63.0m height, capped with a prestressed concrete segmental spherical dome with two large openings to facilitate the replacement of SG should it be needed at later date. The OCS is a reinforced concrete structure having similar shape of that of ICS and covers the ICS completely (Fig.-1). The ICS is designed against the postulated DBA pressure (14.4 T/m^2 (g)) and temperature due the various postulated accident scenario viz. LOCA, MSLB etc.

A non-linear analysis of the IC has been carried out considering the reinforcements & prestressing steel embedded in the concrete in order to study the factor of safety available for the ICS beyond the postulated DBA scenario. The analysis model has been developed using a degenerated layered shell element in which the reinforcements/prestressing steels are modelled using a smeared approach. Various aspects of behaviour of reinforced/prestressed concrete under tension and compression viz. tension stiffening, compression behaviour of the concrete etc., have been accounted for using the state of the art knowledge available in the literature.

This paper presents a comprehensive description of the analytical model used in the evaluation of the ULBC of the ICS under beyond postulated DBA scenario with due consideration to the aspect of analytical modeling of the behaviour of the reinforced concrete shell under tension & compression. The behaviour of the ICS has been presented in this paper at different stages of loading beyond the design pressure. The behaviour of the ICS at different stages of loading beyond the design pressure considering constant accident temperature has also been discussed in this paper. The problem is highly non-linear and the analysis results are sensitive to the FE discretisation of the structure. The adequacy of the FE discretisation considered in the analysis is established by mesh sensitivity analysis. The same is also discussed in this paper. The additional factor of safety of the design of the ICS beyond the postulated DBA with and without accident temperature has been discussed in this paper.

ANALYSIS METHODOLOGY

Geometrical Idealisation

The containment is a thin shell structure. Therefore, the stresses developed due to different loads are mainly membrane in nature and the normal stresses in thickness direction are negligible. Radial (transverse) tensile stresses do develop in the ICS by means of embedded curved prestressing cables (curvature effect). Radial tensile stresses also occur due to transition in thickness of the shell at the discontinuities (transition effect) and due to presence of voids due to cable sheath (stress concentration effect). The radial tensile stresses are more during the construction time and reduce under the internal pressure due to accident condition. Since the magnitude of the radial stresses both under compression and tension is almost negligible under accident condition, a shell model using 8 noded degenerate quadratic shell element has been adopted for evaluating the non-linear response of the structure. Transverse shear deformations are considered in the element formulation with the assumption that the normal to the mid-surface of the element remains straight but not necessarily normal during deformation. Three translational and two rotational degrees of freedom are considered per node. The layering system helps in introducing the reinforcements in relevant layers and also in tracing the progress of cracking through the depth of the shell.

Material Modelling

The materials used are concrete and reinforcing / prestressing steel. Properties of concrete in tension and compression are modelled separately.

Concrete in Tension

Concrete behaves linearly upto its tensile strength. Then it cracks and the tensile stress reduces gradually to zero with increase in strain. The most common procedure to consider this phenomenon is through a stress based cracking criterion in conjunction with a smeared crack model where the cracks in concrete are assumed smeared over the element [1]. Cracks are assumed to form in planes perpendicular to the direction of maximum principal tensile stress as soon as this stress reaches the specified concrete tensile strength f_t. The cracked concrete is anisotropic and the elemental values must be transformed to the global x-y axis [1].

Tension Stiffening

Concrete carries a certain amount of tensile force normal to the cracked plane even after formation of cracks due to its bond effect. The concrete adheres to the reinforcing bars and contributes to the overall stiffness of the structure. Several approaches based on experimental results have been employed to simulate this tension stiffening behaviour. A gradual release of the concrete stress component normal to the cracked plane is adopted in this work. The process of loading and unloading of cracked concrete is also taken care of [1].

Cracked Shear Modulus

Experimental results indicate that a considerable amount of shear stress can be transferred across the rough surface of cracked concrete. Also, the dowel action of steel bars contributes to the shear stiffness across cracks. Tests have shown that the primary variable in the shear transfer mechanism is the crack width, although aggregate size, reinforcement ratio and bar size also have an influence. A common procedure to account for aggregate interlock and dowel action in a smeared cracking model is to attribute an appropriate value to the cracked shear modulus G^c. In the present work a similar approach is adopted, where the cracked shear modulus is assumed to be a function of the current tensile strain [1]. The programme incorporates the closing of cracks, if any, by assuming the un-cracked shear modulus in the respective direction.

Compressive Behaviour of Concrete

The most common approach to model the compressive behaviour of concrete is through a plasticity-based model. This requires a yield criterion and a flow criterion for obtaining the response beyond the yield. A linear elastic, plastic hardening model is generally employed. In the present application a elastic-perfectly plastic model is considered for σ_0 (σ_0 is the ultimate compressive strength under uni-axial compression) since the shell is stressed predominantly in tension and additional computations required when using a strain hardening model can be avoided. Concrete is assumed to be elastic till the equivalent stress reaches the uni-axial compressive strength of the material. From then on, perfect plasticity is assumed.

Yield Criteria

In the present analysis using thick plate and shell elements, transverse shear effects are taken into account and therefore, a tri-axial yield criterion is employed [1]. This criterion is formulated in terms of the first two stress invariant (I_1 and J_2) and two material properties (α and β) which is related to equivalent effective stress from a uni-axial test (σ_o). Since the stress normal to the plate (σ_z) is negligible, the state of stress is bi-axial. The uni-axial compression test and the bi-axial test under equal compressive stresses ($\sigma_1 = \sigma_2$) are used to define the material constants. For practical purposes, a relation can be assumed between the equal bi-axial yield stress (f_{cb}) and the uni-axial yield stress ($f_c^{'}$). In that case, the yield condition is a function of only one material parameter ($f_c^{'} = \sigma_o$) which is the most reliable constant to characterise the concrete behaviour and easily obtainable from test results. The expression obtained is also compared well with the experimental results of Kupfer et al. in bi-axial stress field. An elastic response is assumed up to the effective stress value of $f_c^{'} = \sigma_o$, after which a perfectly plastic response follows until crushing is reached.

Flow Rule

The associated flow rule is considered predominantly for concrete for practical purposes. The plastic strain increment is defined as the multiplication of the magnitude of the plastic strain increment and a gradient that defines the normal direction of this plastic strain increment to the yield surface. The yield function is dependent on the instantaneous stress values.

Crushing Condition

Crushing type of concrete fracture is a strain-controlled phenomenon. Crushing of concrete occurs when the compressive strains (in terms of effective strains) exceed the ultimate strain specified. The ultimate strain specified in this work is 0.0035 when the material is assumed to lose its entire characteristic strength and rigidity.

The detailed formulations of all the above phenomena are described in detail in Ref. [2].

Reinforcing and Prestressing Steel

The reinforcing bars/prestressing steel tendons are considered as steel layers of equivalent thickness in the present model. Each steel layer has a uni-axial behaviour resisting only the axial force in the bar direction. A linear elastic and plastic hardening behaviour is assumed for the reinforcing/prestressing steel.

MESH SENSITIVITY ANALYSIS OF ICS

The problem of evaluation of ULBC of ICS is highly non-linear. The analysis results are sensitive on factors like, FE discretisation, the tolerance specified for convergence of results etc. Analyses have been carried out to establish the adequacy and stability of the FE discretisation to carry out the present non-linear analysis.

A Finer FE discretisation of ICS has been developed in order to demonstrate the stability of FE mesh. One quarter of the ICS is modelled for analysis. One quarter of the model is chosen to contain the problem size of the finer mesh. The refined mesh is around three times finer than the coarser mesh. Complete fixity is considered at the base of ICS and symmetric boundary conditions are applied along the line of symmetry. The structure is analysed with self-weight as constant load and internal pressure as varying load. No prestressing load is considered in this study. Very stringent load steps are employed to obtain the load-deformation curve. The internal pressure is increased in steps till the analysis is failed to converge even with a very small load step. The load-deformation curve of both coarser and finer model near the SG opening where maximum deflection has been observed (Fig.-2) are compared and have been found to match very closely. Hence, the FE mesh considered in the present project is considered to be stable and adequate.

THE NON-LINEAR ANALYSIS

The Non-linear Analysis without considering Accident Temperature

One half of the ICS is modelled to exploit the symmetricity of the structure. The ICS is connected to the 5.5m thick massive raft at the base. Hence, complete fixity has been assumed at the base of the ICS. The ICS is subjected to two types of loading i.e., constant load consisting of prestress and self weight of the structure and variable load consisting of internal pressure. The temperature load corresponding to the accident condition has not been considered in this study. The internal pressure, representing the accident pressure needs to be applied gradually. Hence, special provision is made in the FE programme to increment only the internal pressure.

Initial elastic analysis is performed applying an initial load increment. Strains and stresses are computed. Separate routines are used to compute the current material properties of the uncracked, cracked concrete layers and elastic or plastic steel layers. After the evaluation of the current properties, stresses are computed and integrated to obtain residual forces. The current material state is stored.

The residual forces thus obtained represent a deviation from equilibrium. Convergence of the iteration is checked with respect to norm of displacements and permissible tolerance. If the convergence is not satisfied, the residual forces are applied back on the structure and the above solution process is repeated. If the convergence is achieved, then the next load increment is applied. Stiffness matrices are recomputed and the process is repeated. It may be noted that the stiffness matrix is formulated at the beginning of each increment. In addition, it is reformulated after specified number of iterations to accelerate the convergence.

To have a control on the load increment size, the modified Newton - Raphson procedure is employed. Load increments have been varied as the internal pressure increases. Initially, a load increment of 0.5 - 0.25 times the design pressure has been considered upto the design pressure. Subsequently, the load increments have been varied from 0.2-0.01 times the design pressure till the failure load is reached. A tolerance of 5 % of displacement norm is found to be satisfactory. [1]. However, to avoid any divergence of results in the initial portion of the load deformation curve, a stringent tolerance of 0.5% of displacement norms is applied. Since it is difficult to achieve this tolerance near failure load, a higher tolerance of 2% has been used.

The Non-linear Analysis considering Accident Temperature

Similar to the above analysis, one half of the ICS is modelled. Fixed boundary condition is assumed at the base and symmetric boundary condition is assumed at the line of symmetry of the ICS. The temperature profile across the thickness of ICS beyond postulated DBA scenario is not available. Hence in order to study the effect of accident temperature on the ULBC of the ICS, the accident temperature profile across the thickness of ICS during postulated DBA is considered as constant load along with other constant loads, e.g., self-weight and prestress. The loads due to accident temperature will thus, not be incremented along with the internal pressure.

The analysis procedure is similar to that without considering the accident temperature. Initially, a load increment of 0.1 times the design pressure has been considered up to the design pressure. Subsequently, the load increments have been varied from 0.05-0.025 times the design pressure till the failure load is reached. To avoid any divergence of results in the initial portion of the load deformation curve, a stringent tolerance of 0.5 - 3% of displacement norms is applied. A higher tolerance of 4 - 5% has been used beyond the design pressure in the non-linear zone of the load-displacement curve.

ANALYSIS RESULTS

Response of Structure under Internal Pressure

The non-linear analysis considering dead load & prestress load (as constant load) and dead load, prestress load & load due to accident temperature (as constant load) have been carried out considering a single load increment. The response of the structure upto an internal pressure of 1.4 times the design pressure is linear when accident temperature is not considered in analysis, while the same is 1.2 times the design pressure when accident temperature is considered in analysis.

Response of Structure at the Initiation of through-and-through Cracking

The initiation of the through-and-through cracking is observed at an internal pressure value of 1.425 times the design pressure when the accident temperature is not considered, while the same is observed at an internal pressure value of 1.4 times the design pressure when accident temperature is considered in analysis. However, the cracking has been detected very locally around SG opening in ICS dome. The extent of through-and-through cracks for analyses carried out without and with accident temperature is shown in Fig.-3 and Fig.-4.

Response of Structure at the time of Initiation of Reinforcement Yielding

The initiation of yielding of reinforcement steel is observed at an internal pressure value of 1.75 times the design pressure when accident temperature is not considered, while the same is 1.475 times the design pressure when accident temperature is considered in analysis. The yielding of reinforcing steel is observed on the outer face of the dome near the SG opening.

Response of Structure prior to Failure

The response beyond the load factor of 1.60 is highly non-linear when accident temperature is not considered in analysis. The similar trend of load-deformation curve is observed at the load factor of 1.65 times the design pressure when accident temperature is considered.

When accident temperature is not considered, the analysis failed to converge beyond a load factor of 2.08 due to excessive yielding of reinforcements in the dome region mainly in the thickened portion of the dome region around the SG opening. The extent of through-and-through cracks at the time of failure is shown in Fig.-5.

When accident temperature is considered, the analysis failed to converge beyond load factor of 1.9. In this analysis also excessive yielding of reinforcement in the dome around SG opening thickened region is observed. The extent of through-and-through cracks at the time of failure is shown in Fig.-6.

DISCUSSION OF ANALYSIS RESULTS

The load-deformation curve of the ICS is presented at two locations, e.g., at crown of the ICS dome and at the location of maximum deflection near SG opening in ICS dome. It is observed from the load-deformation curves of these locations that while the behaviour of the area around SG opening is highly non-linear, the crown of the dome (that represents the general shell area of the ICS) behaves almost linearly even prior to failure. Fig.-7 and Fig.-8 show the plot of load-deformation curve of ICS under internal pressure at the two locations mentioned above without and with accident temperature respectively. It is observed from the load-deflection curve that the response of the ICS is linear between points 1 and 2. Initiation of reinforcement yielding starts at point 3. Through the thickness cracking is observed at point 4. The structural failure takes place at point 5 at a load factor of 2.08 when accident temperature is not considered and at a load factor of 1.9 when accident temperature is considered.

CONCLUSION

It is concluded that the primary containment of a typical 540MWe Indian PHWR can withstand an internal pressure of 1.9 times its design pressure before structural failure. The mode of failure in the structure is due to excessive yielding of reinforcements.

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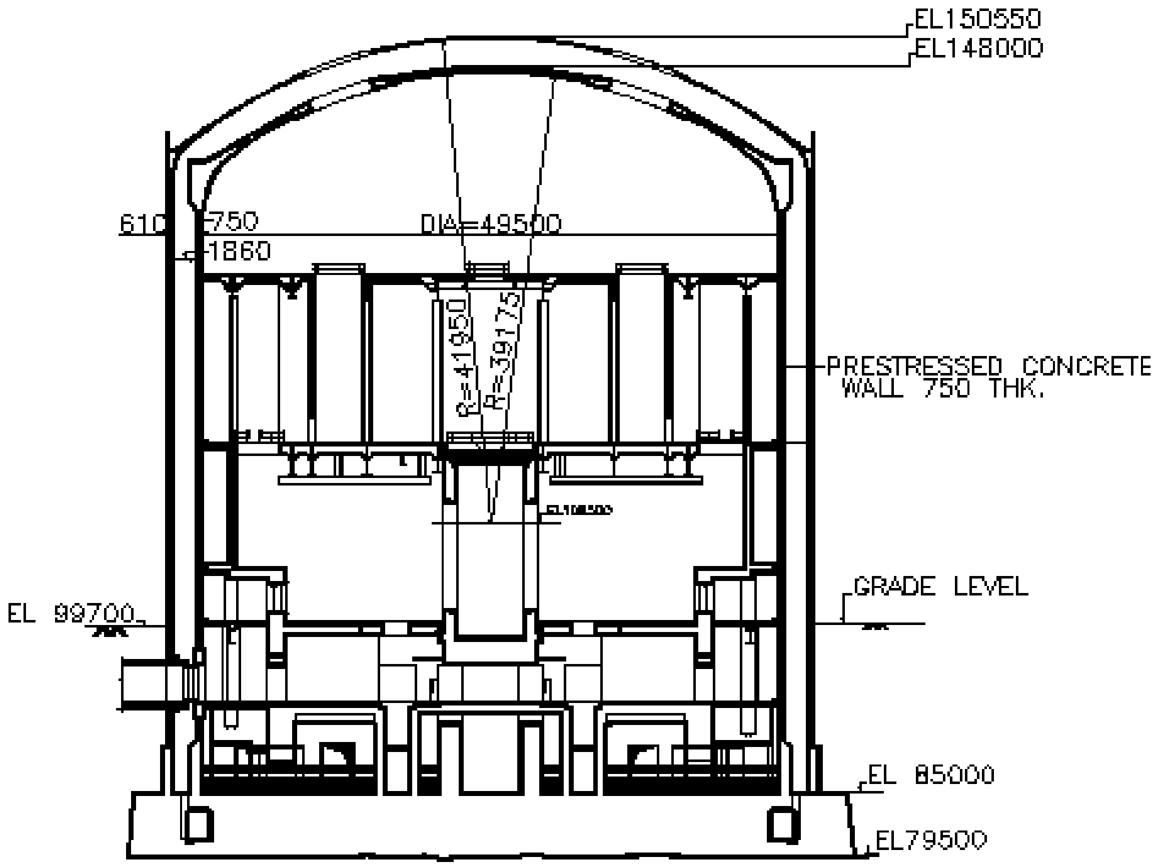

Fig.-1 : General Arrangement of Containment

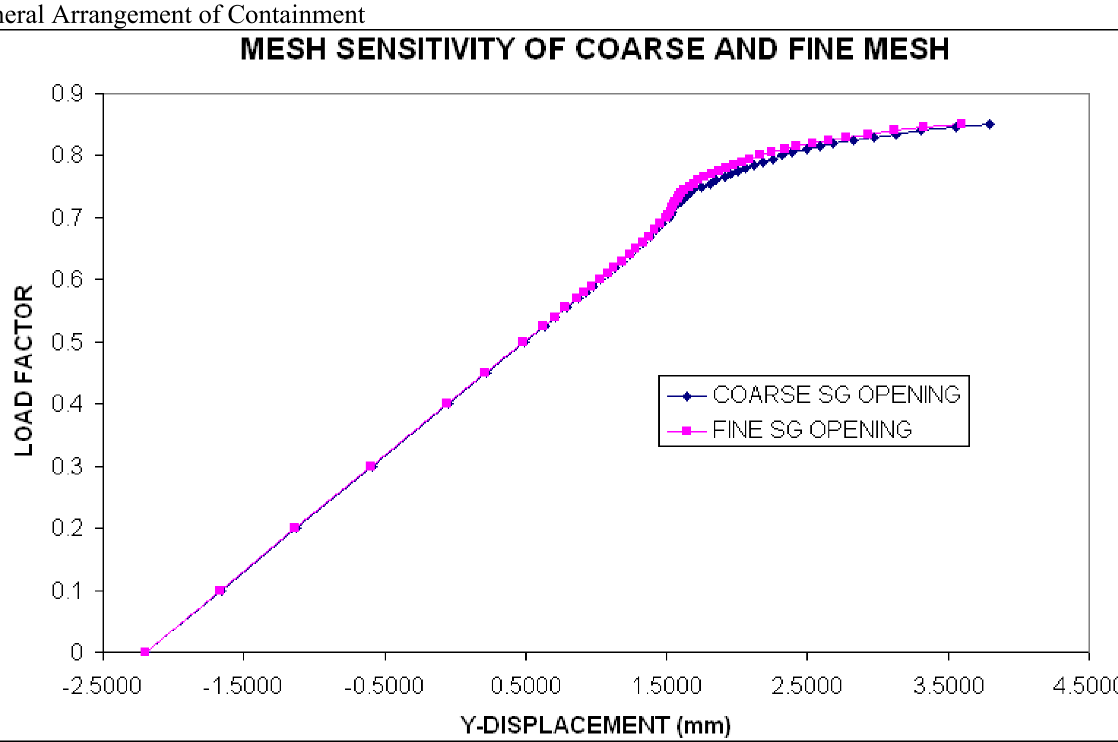

Fig.-2: Load-deformation curve of Crown and near SG opening for Mesh Sensitivity Study

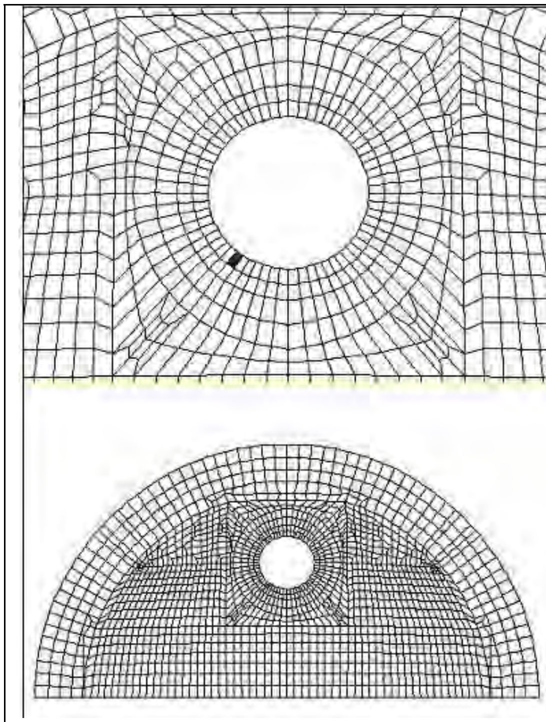

Fig.-3: Initiation of thru'_n_thru' crack (at Load Factor = 1.425) without Accident Temp

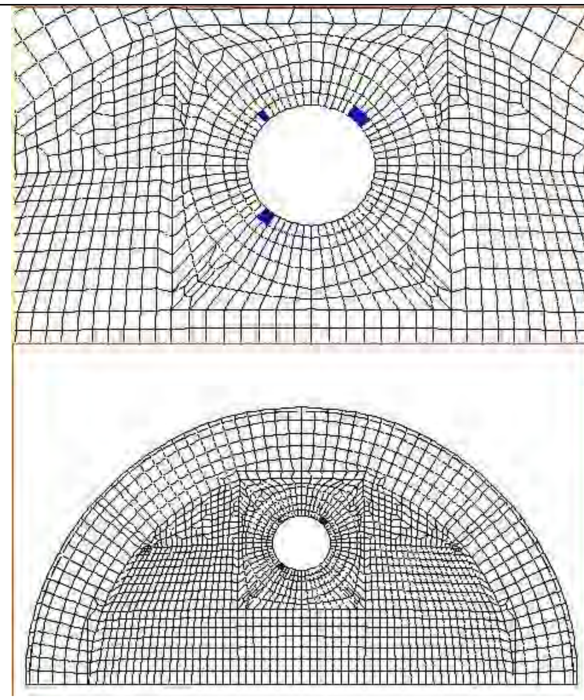

Fig.-4: Initiation of thru'_n_thru' crack (at Load Factor = 1.4) with Accident Temperature

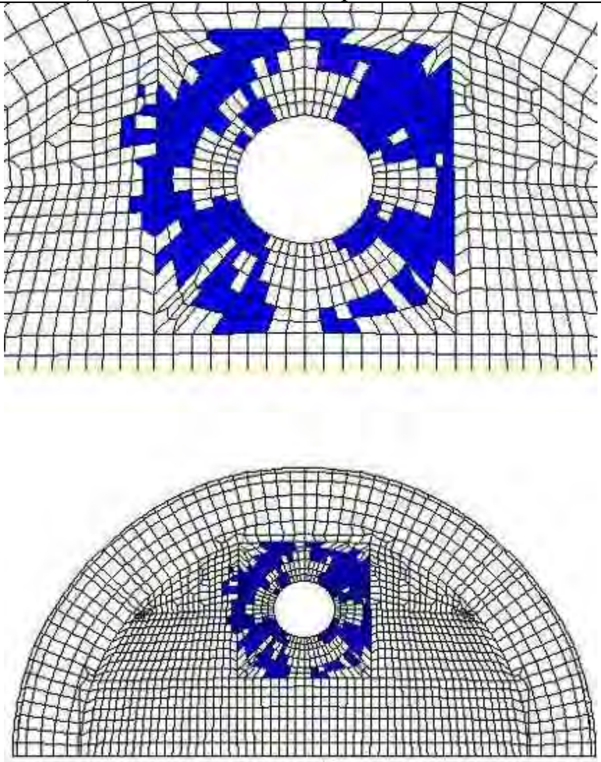

Fig.-5: Extent of thru'_n_thru' crack at failure (at Load Factor = 2.08) without Accident Temperature

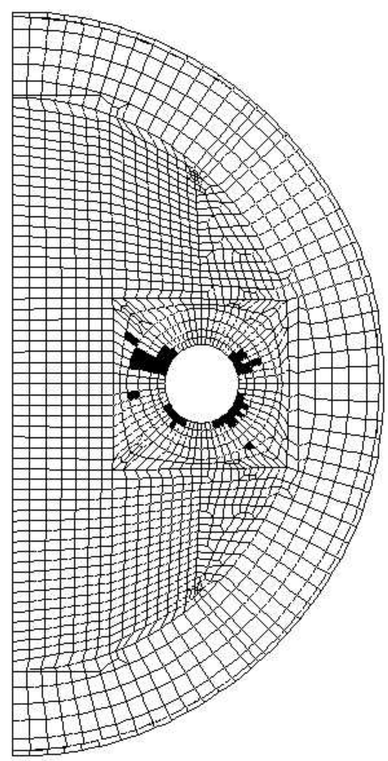

Fig.-6: Extent of thru'_n_thru' crack at failure (at Load Factor = 1.9) with Accident Temperature

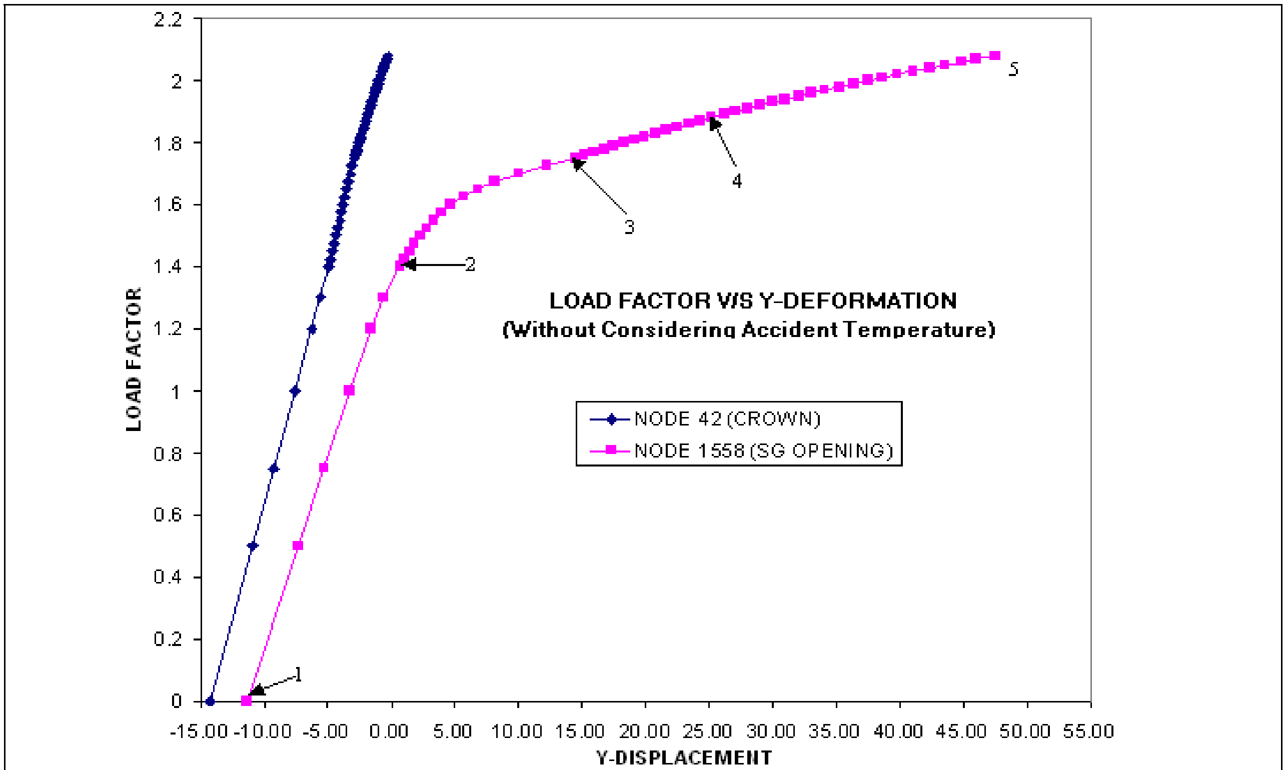

Fig.-7: Load-deformation curve of the ICS without Accident Temperature

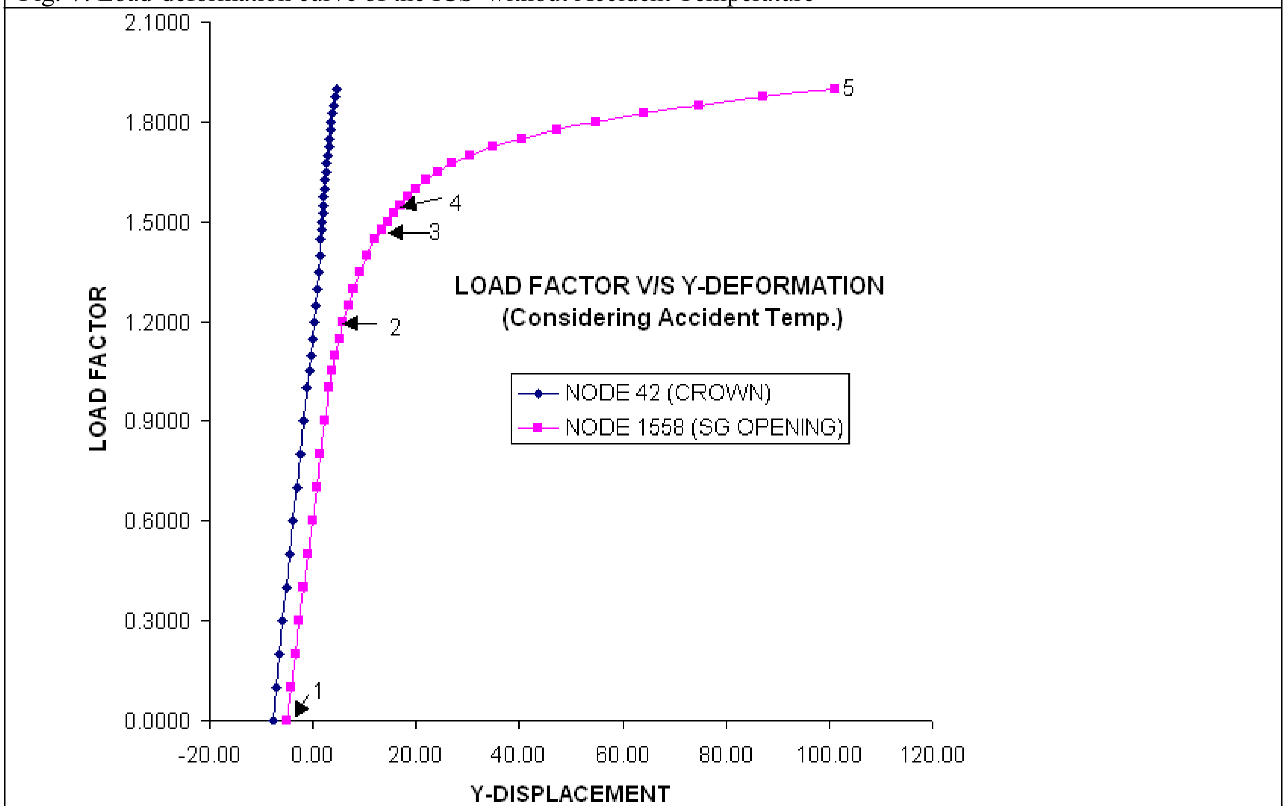

Fig.-8: Load-deformation curve of the ICS with Accident Temperature

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