Transactions of the 17th International Conference on
*Structural Mechanics in Reactor Technology (*SMiRT 17)
Prague, Czech Republic, August 17 –22, 2003

Paper # H04-5

Strength Analyses of Containment Steel Liner at the Plasticity Instability

Vladimir I. Klyashchitskiy[1)], Vladimir I. Golyakov[1)], Victor I. Kostylev[2)], Boris Z. Margolin[2)]

[1)] Atomenergoproekt, Moscow, Russia
[2)] Central Research Institute of Structural Materials (CRISM) "Prometey", Saint-Petersburg, Russia

ABSTRACT

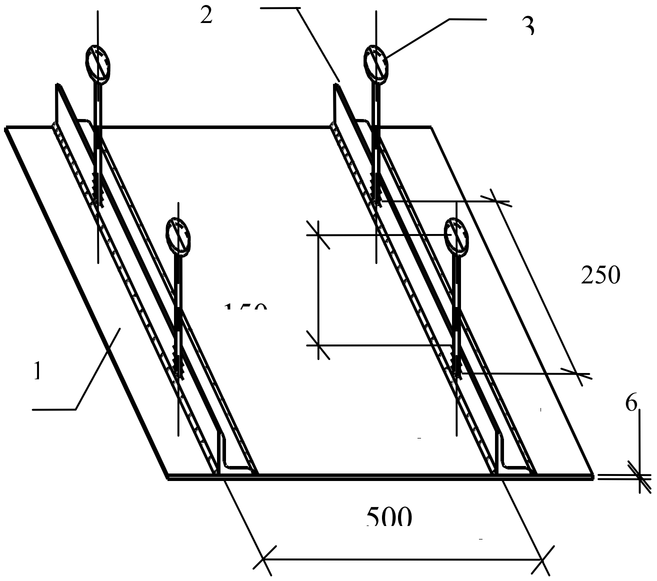
The steel liner of NPP containment plays the important role of a leaktight contour preventing the possible releases of radioactive substances beyond the boundaries of the reactor building. However, so far in many cases an assessment of strain-stress state of the liner having initial imperfections of the shape was made with approximate methods. A new methodology for the analysis of the liner at the plasticity instability was developed at Atomenergoproekt institute in cooperation with specialists from other agencies. The methodology is based on code "Termit". Assessment of the critical strain was made taking into account possible presence of one or two defects: construction undercut or crack-like defect in a weld. On the base of the real structure analyses under any combinations of quasi-static loads the algorithm was developed for the computation of the liner.

KEY WORDS: containment, liner, anchor, imperfections, elastic-plastic deformation, crack, critical strain, weld, J-integral, analysis, code, accident, sheet shape, pressure, shortening of concrete, temperature, algorithm.

Mainly thin steel liner ensures leak-tightness of inner space of reinforced concrete containment and prevention of radioactive substance release into the environment.

From the design point of view, the liner is a system of sheets, anchoring elements and embedded parts. Anchors ensure joint deformation of sheets and underlying reinforced concrete layer and are made, mainly, of angles and/or bars strengthening at the ends. The European option is to weld up the angle ribs to the sheets using bar dowels welded between the angles; the Russian option is to weld up one flange of an angle with the reinforcement bars being welded to another flange (Fig. 1).

During rolling and/or erection operations, certain parts of a sheet may develop considerable imperfections of various shapes, including undulating form directed inside the containment. In the prestressed containment concrete contraction develops, this results in loss of sheet stability in these areas (the behaviour transfers to the supercritical phase) and then plastic strains occur. Therefore, the structural integrity (impossibility of crack propagation) of the liner in the elastic-plastic phase is used for the assessment of its functional adequacy (leak-tightness).



1-sheet, 2-dowel, 3-angle.
Fig. 1. Example of a containment liner sheet anchorage design

CODE TERMIT

V.I. Golyakov created a special code «Termit» for computation of the liner supercritical behaviour under any combinations of quasi-static loads that may occur during operation in the leak-tight spaces. The code was tested by means of a number of comparative calculations having known analytical solutions obtained by the structural mechanics methods [1,2], a comparative calculation carried out by the CRISM "Prometey" experts according to their own code and experimental tests.

The calculation model used in the code is a strip of a liner sheets longitudinally secured to concrete by a row of anchors, with the sheet strain in the transverse direction being constrained (Fig. 2). Strain-stress curve of the sheet are given by uniaxial diagram, which includes a hardening phase. The stress state of the liner in each node of calculation is biaxial.

The stress-strain relationship is elastic until yield surface described by the Mises-Henki criterion is reached [3, 4]. The problem of liner calculation is stated dynamically. Liner sheet displacement equations are solved using the finite-difference method. Displacement equations are the relationships of the theory of thin flexible shells [5]. One of the important features of the problem under consideration is the need to describe adequately the liner panel loss of stability phenomena. This case was simulated through the geometrically non-linear formulation of the shell theory relationships with the curvature varying with length and time. In the calculation, the loss of panel stability condition is characterized by the occurrence of a non-equilibrium dynamic state. External loading of the liner is suspended for the period of the system transition to a new equilibrium state.

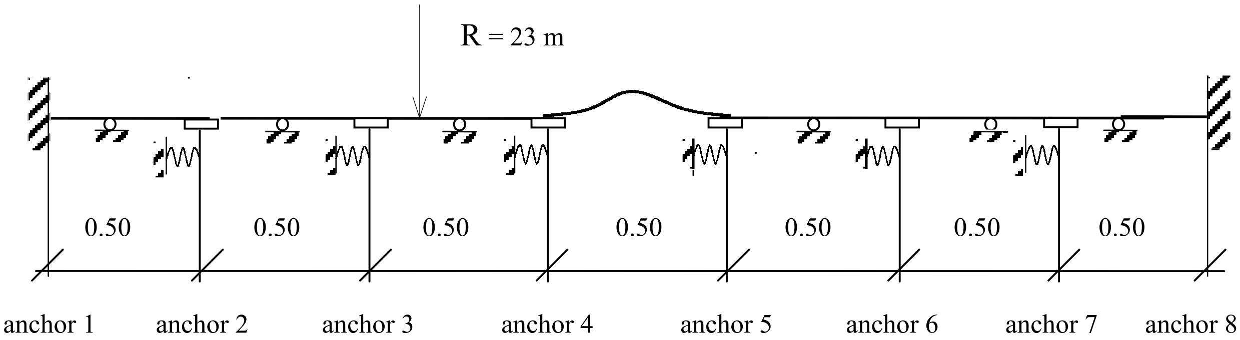


Fig. 2. Computational physical model

All processes in the computation are considered against a conventional time scale. It is based on the necessary machine time of the system achieving the equilibrium state at each level of calculation. The calculation is carried out in several steps. The liner stress-strain state achieved at the end of each step is the initial condition for the next step.

The liner sheet-to-anchor interaction is simulated by the application of forces at the anchor locations. Shear characteristics of the anchors are given with coefficients of a non-linear function.

At calculation step 1, initial camber of a liner panel is generated, with the initial camber shape described by a cosine function. Since initial camber develops during the sheet rolling, it is assumed that there is no stress in the sheet. There is no stress in the anchors, either.

Calculation step 2 shows liner behaviour during concreting. Liner sheets exert the uniformly distributed per the surface pressure on the liner sheet. It is also assumed that the anchorage nodes are not displaced. When the step is complete, position of the concrete surface is fixed, and it coincides with the liner camber shape. At the further steps of calculation, liner sags crossing this surface are prohibited.

In the transverse direction, the liner sheet is in a plane strain state. Transverse strain is the same along the whole liner length; it is generated at calculation steps 3 and 4 (strain due to concrete contraction, shrinkage, creep).

At calculation step 3, longitudinal and transverse sheet deformations due to the deformation of the underlying concrete layer are generated at each calculation node. At this step, the extreme anchors are restrained, while others are displaced due to internal forces in the sheet occurring during simulation.

Calculation step 4 computes the simultaneous effect of the sheet thermal heating and external pressure. Functions of temperature and positive pressure variation with time may be given in the form of profile.

CALCULATION TEST

A code in use at CRISM “Prometey” was adopted as an analogue for testing. B.Z. Margolin and V.I. Kostylev carried out calculation of the test. Calculation models were constructed using the respective means of each code.

Differences in deflections and strains obtained from both codes make an average of 15%, which should be considered a very good agreement, especially taking into account complexity of the problem being solved. The difference lies mainly in evaluation of the membrane strains, with the “Termit” code being more conservative in the evaluation of the tensile strains and deflections and the “Prometey” code – in the evaluation of compressive strains. Differences in stresses are more essential – they reach 20%, due to the different stressed state models. However, this does not have a significant effect on the strain evaluation due to an insignificant fraction of elastic strain in the total strain magnitude.

APPLICATION METHODOLOGY FOR ASSESSMENT OF THE CRITICAL STRAIN OF THE WELDED JOINTS

This methodology was proposed by the B.Z. Margolin and V.I. Kostylev. Two types of welded joint defects were considered for typical liner structures of the concrete containment: construction undercut (between angle anchor and sheet) or crack-like surface defect in the weld or in heat affected zone.

Calculation models are given in Fig. 3-4. The stress-strain fields is determined in corner weld at the external loading by the finite element method [6]. Then the J-integral Eshelbi-Cherepanov-Rice is calculated numerically [7-8].

Taking into account the dependence of critical value of J-integral - J_C on temperature[9], the dependences of nominal strain on temperature for bending and tensile loading were obtained.

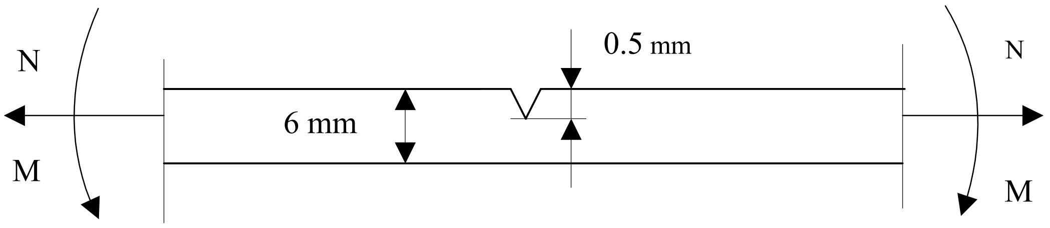


Fig.3. Calculation model for a sample with a like crack defect in a sheet or butt weld

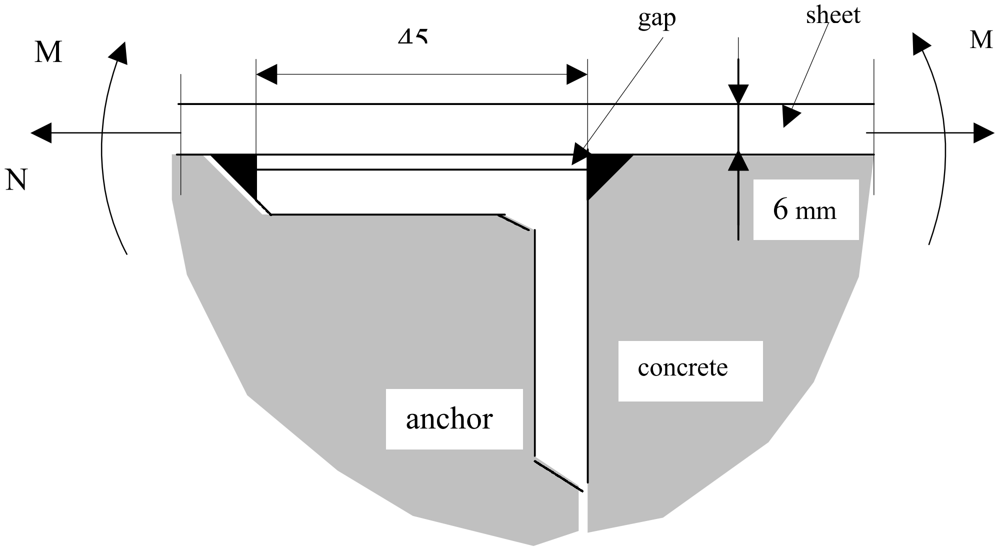


Fig. 4. Calculation model for a sample with construction gap

The critical values of the nominal strains in a sheet are calculated based on the prior experimental critical values of J-integral for respective materials (Jc). The J-integral critical value for carbon steel is adjusted with regard to the heating temperature. Thus relationship between J-integral and nominal bending and membrane strains in the vicinity of a crack are established.

These critical values are then reduced by dividing them with margin factors 1.4, 1.2 and 1 – accordingly for the operating, design- bases accident and beyond-design-bases accident conditions [101].

As a result, the static strength condition is proposed [11].

$$\frac{\varepsilon_{buckl,i}}{\varepsilon_{buckl,d}} + \left(\frac{\varepsilon_{memb,i}}{\varepsilon_{memb,d}}\right)^2 \leq 1.$$

Table 1. Critical allowable strains in a steel sheet

Conditions	Temperature ^0C	Allowable strains, %				J-integral margin factor
		undercut		construction gap		
		membrane $\varepsilon_{memb,d}$	buckling $\varepsilon_{buckl,d}$	membrane $\varepsilon_{memb,d}$	buckling $\varepsilon_{buckl,d}$	
1. Pre-Startup and Operating:	20	1,8	1,5	8	2,9	1,4
	≥40	3,6	2,5	8	3,7	

2. Design Basis Accident	≥40	4,3	2,9	8	4,0	1.2
3. Beyond Design-Basis Accident	≥40	5,4	3,5	8	4,4	1

Where: $\varepsilon_{memb,i}$ and $\varepsilon_{memb,d}$ -are relative membrane strains of the sheet, obtained from calculation and maximum allowable respectively;
$\varepsilon_{buckl,i}$ and $\varepsilon_{buckl,d}$ - are relative bending strains of the sheet, obtained from calculation and maximum allowable respectively.

Ultimate allowable strain values in a sheet of C255 steel (6 mm thick) calculated according to this methodology using J-integral margin factors are given in Table 1.

EXAMPLE OF THE CALCULATION

The methodology proposed is illustrated with the results of the calculation for the new design WWER-1000 NPP containment liner structure.

The underlining surface is a cylinder 23 m in radius. Sheet thickness is 6 mm, anchors are angles 63 x 6 at a spacing of 0,5 m.

A row of 7 spans was considered, with the middle span having initial camber equal to 1/300 of a span between anchors.

Concrete grade is B45. Sheet thermal expansion coefficient is $0{,}123\times10^{-4}$ $1/^{0}C$.

Concrete shortening are 60×10^{-5} in the longitudinal and 40×10^{-5} in the lateral direction.

The yield strength of steel was accepted equal to the average value 260 MPa.

Anchor shear resistance diagrams were accepted as recommended by the Czech research institute for aboveground construction.

Main loads are: concrete mix pressure, anchors effects due to containment concrete shortening, accident pressure and temperature, pre-startup and post-accident vacuum (Fig. 5).

Results of the calculation are shown in the plots below.

Liner loses stability only in the middle span having a significant initial camber of the sheet. In the course of increasing pressure application, the accepted sinusoidal initial shape of sheet transforms to the shape of a ridge (Fig. 6). Largest shear forces are produced in the anchors adjacent directly to this span (Fig. 7, 8). Maximum values of the fiber strain are generated in the central part of the middle span sheet (Fig. 9, 10).

Loading sequence is of particular importance for the spans where the sheet loses stability and transfers to the elastic-plastic phase of metal, since the load superposition principle does not apply in this case. Besides that, the stress-strain state is largely and ambiguously affected by the values of the applied loads. As with any other random process, these values may vary within a significant range, depending on the time-history containment concrete and the accident scenario (pre-accident temperature, accident pressure and temperature).

The calculations performed considered the potential load range bounded above and below. Since, for the anchor effect, the yield strength value (and metal hardening) mainly plays the role of a load.

The initial camber itself is not a load; however, its value may have a significant effect on the supercritical behavior of a liner sheet. With regard to the specifics of the code “Termit” algorithm, this magnitude was accepted in the calculation to be equal to the minimum value required for the sheet losing irreversible stability.

Review of the calculation results for the accepted containment liner structure allowed to make certain conclusions as to the effect of loads on the potential of the liner structure to achieve limit states both in sheet strains and anchor strength. Table 2 and the algorithm (Fig. 11) below show the results of this review[*].

What is the most interesting oft these results is the found significant effect of pre-accident temperature of the sheet and initial contraction strains of the underlying concrete (in case of the sheet supercritical behavior, even after the pressure is applied) on the maximum strains in the sheet in the accident condition. It was established that the lower are the absolute values of these factors, the larger are the maximum sheet buckling strains in the accident condition. Therefore, a certain sequence of load application with certain variations of the lower and upper bounds of their values should be followed to obtain conservative estimates.

CONCLUSION

A new methodology for the calculation of functional adequacy of the steel liner of the protection NPP structures was developed. It is based on the evaluation of liner leak-tightness depending on the cracking resistance of welded joints, which, in turns, is evaluated according to the criterion of the critical allowable nominal strain in the adjacent area of the sheet. The methodology utilizes a specialized stress-strain state calculation code “Termit”. The proposed

---

[*] In Fig 11 dotted lines show most unfavorable sequence loading for sheet strains and anchor strengths accordingly.

methodology was proven by means of the calculations and tests. The new methodology allows for a significant increase of reliability of the steel liner design.

The adopted steel liner design for the prestressed concrete containment meets the requirements for the preclusion of the occurrence in the design basis accident mode of the limit states both due to the forces in the most stressed anchors and strain in the area nearby a weld in the central part of the span, these requirements being met in a wide range of design load combinations.

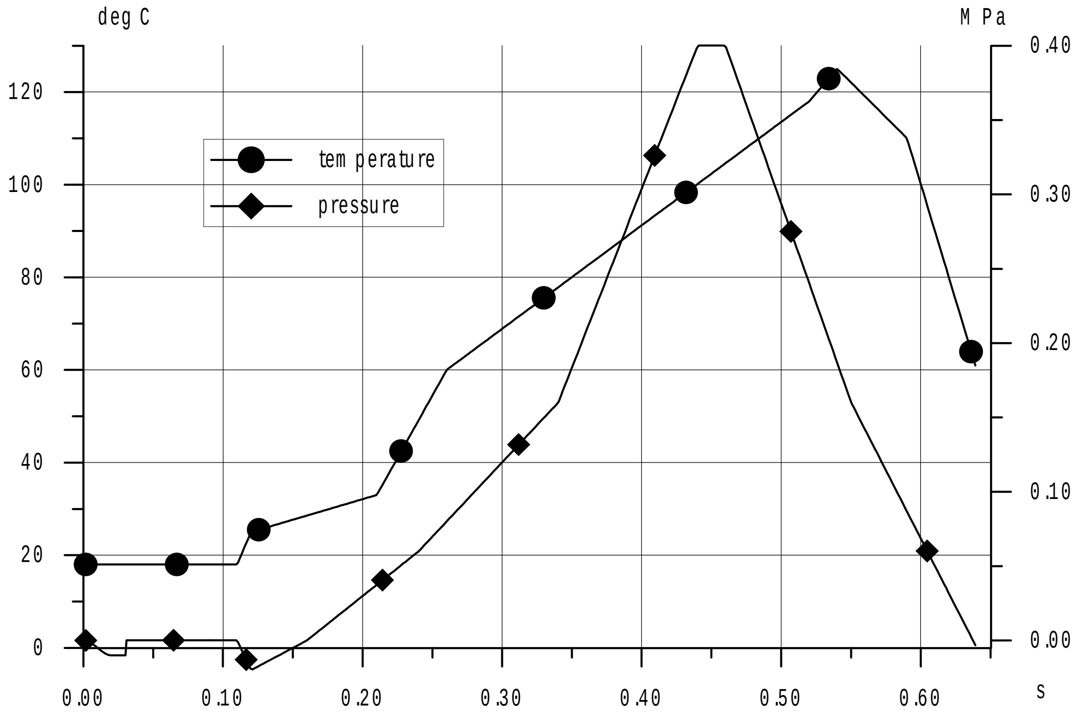


Fig. 5. Computational time history of temperature and pressure for the case of design basic accident

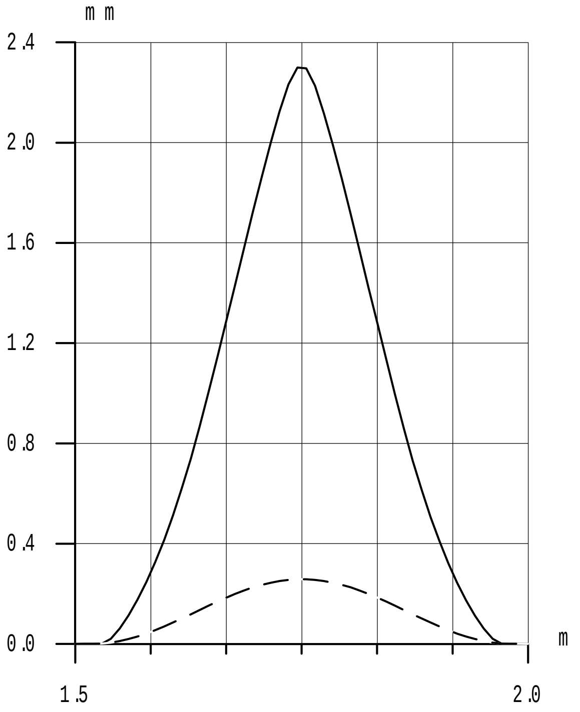


Fig. 6. Variation of the central span sheet shape from the normal operation (- - -) to the accident conditions (-----). Calculated curves correspond to the peak of the temperature, see Fig. 5

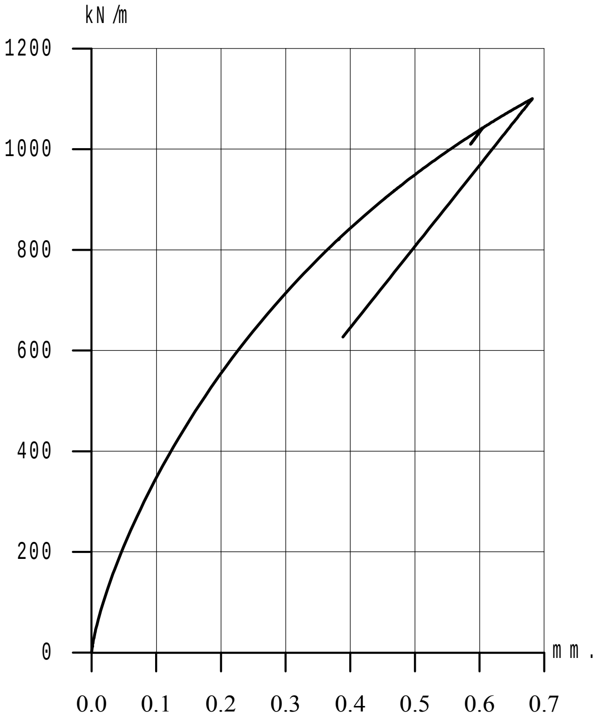


Fig. 7. Fig. 8 Force versus displacement diagram (anchors No. 4, 5)

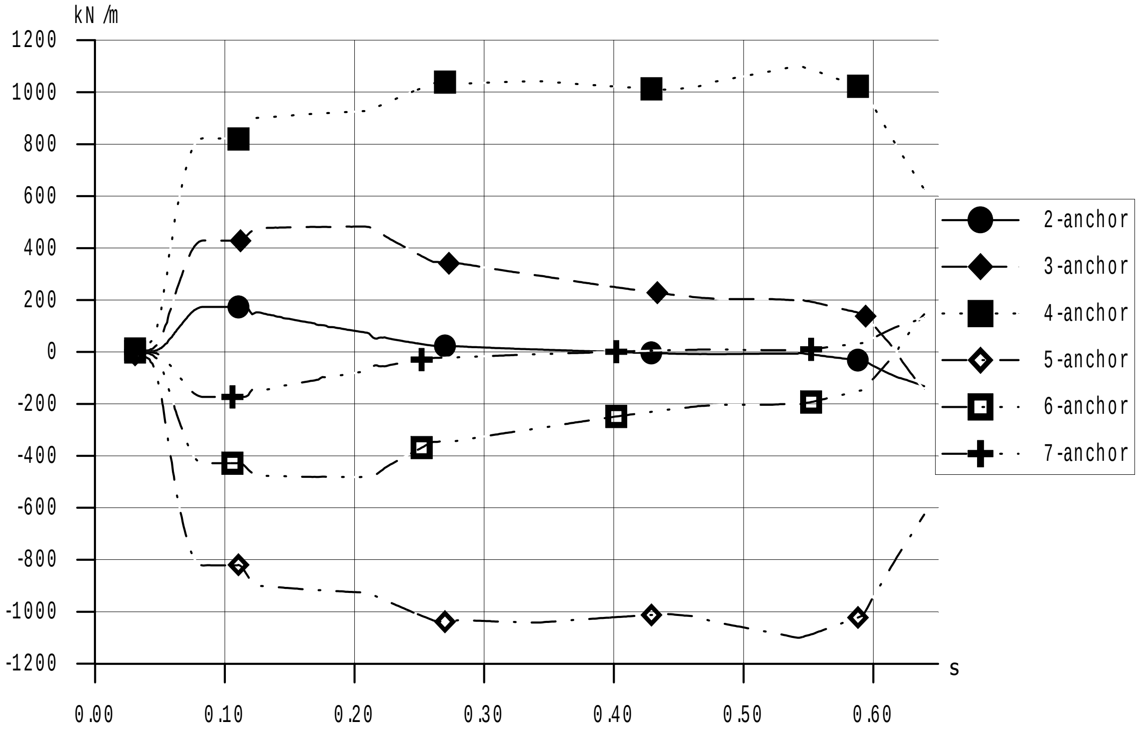


Fig. 8. Anchor force variation during initial loading and design basis accident

Fig. 9 Maximum strain history in the middle span sheet

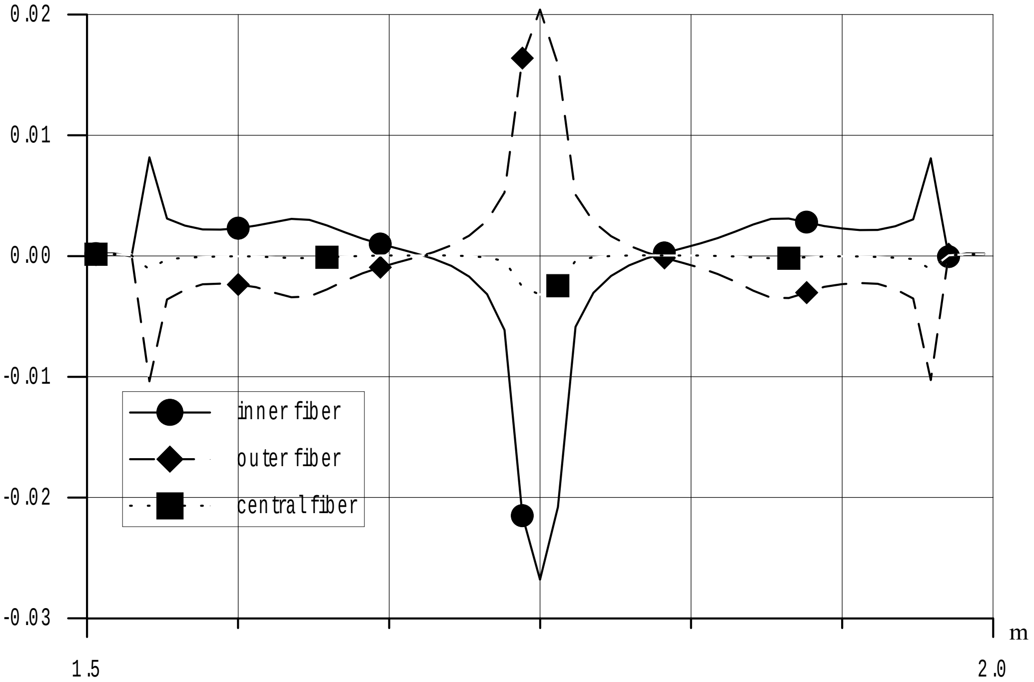


Fig. 10. Strain distribution along central span at the peak temperature (see Fig. 5)

Table 2. Qualitative estimation of actual factors affecting on the strain and force in the containment

Actual factors	On the sheet strains	On the anchor force
1. Initial camber	min**	*
2. Realistic strength of steel sheets	min	max
3. Pre-accident shortening of concrete	min	max
4. Pre-accident*** sheet temperature	min	*
5. Accident pressure and sheet temperature	max	max

* - insignificant effect;
** -deflection causing irreversible loss of stability;
***- temperature at the moment of steep rise of positive pressure.

REFERENCES

1. Grigorenko, Ya.M. and Kryukov, N.N., Numerical solution of the variable parameter problems in flexible lamellar shell statics, Kiev, Naukova dumka, 1988.
2. Volmir, A.S., Deformed system stability, Moscow, Nauka, 1967.
3. Novatsky, V.K., Wave problems in the theory of plasticity, Moscow, Mir, 1978.
4. Ivlev, D.D. and Bykovtsev, G.I., Theory of the hardening plastic body, Moscow, Nauka, 1971.Grigolyuk E.I., Kabanov V.V., "Stability of shells", Moscow, "Nauka", 1978.
5. Kostylev, V.I. and Margolin, B.Z., "Solution of the dynamic elastic-plastic problem in fracture mechanics using finite-element method. Report 1. Dynamic elastic-plastic problem", Strength problems, N7, 1990, pp. 6-12.
6. McMeeking, R.M., "Finite deformation analysis of crack tip opening in elastic-plastic materials and implications for fracture initiation", J. Mech. Phys. Solids, 25, 1977, pp. 357-381.
7 Eshelby, J.D., "The elastic energy-momentum tensor", J. of Elasticity, 5, 1975, pp. 321.
8. Rice, J.R., "A path-independent integral and the approximate analysis of strain concentration by notches and cracks", J. Appl. Mech., 35, 1968, pp. 379-386.
9. Strength calculation code for the equipment and pipelines of nuclear power facilities, Moscow, Energoatomizdat, 1989.
10. Rules for the design and manufacture of mechanical components for the PWR NPPs, RCC-M. Section 1-Subsection Z. Supplement ZG (France). 1995.
11. Malinin, N.N., Applied theory of plasticity and creep, Moscow, Mashinostroenie, 1968.

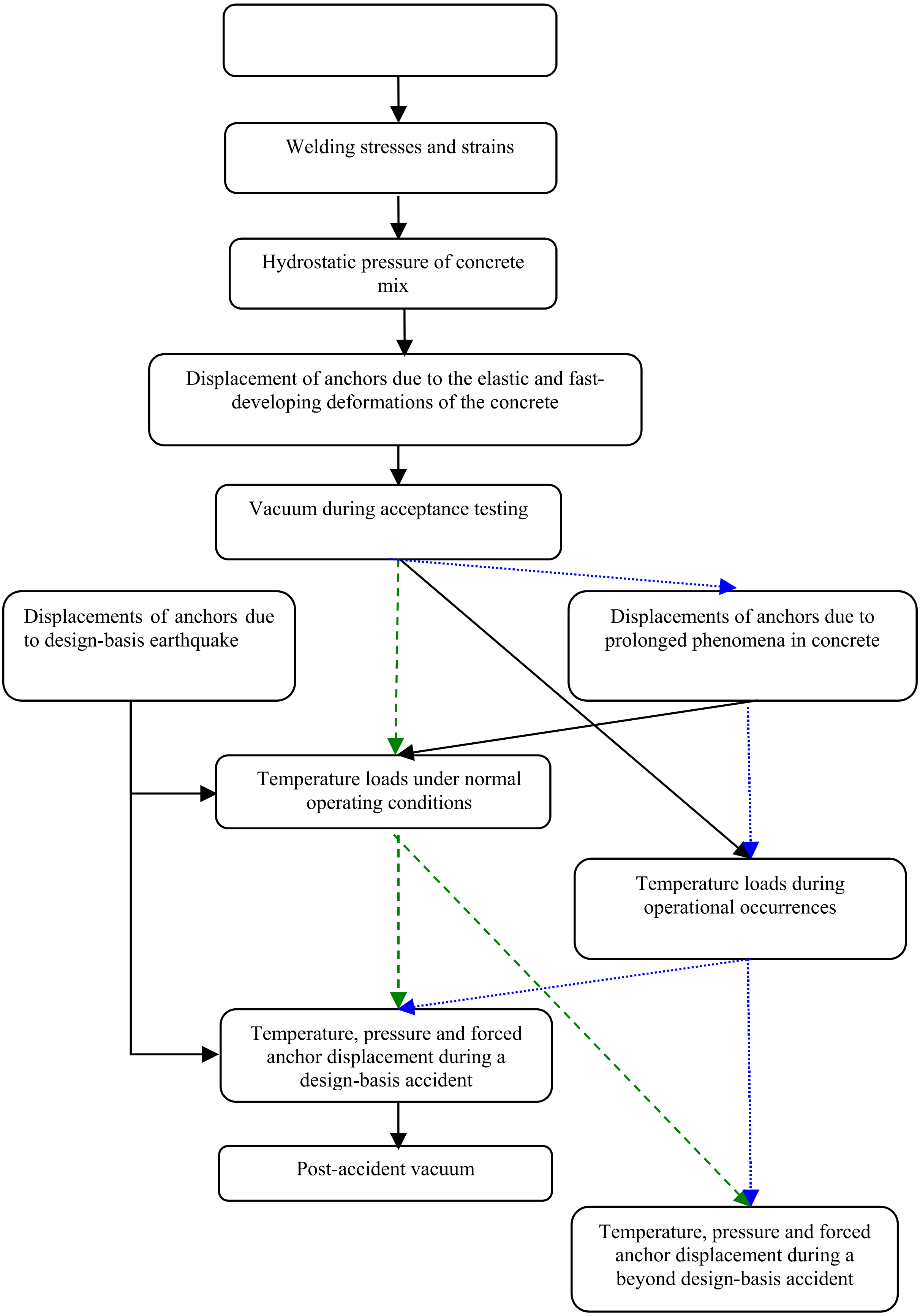


Fig. 11. Algorithm of load application to the containment liner