A REALISTIC STRUCTURAL ANALYSIS OF THE INTEGRITY OF THE LINER OF REINFORCED AND PRESTRESSED CONCRETE CONTAINMENTS

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The BWR Gundremmingen II is the first German nuclear power plant with a concrete containment having a thin steel plate liner directly attached to the interior concrete surface to provide an air-tight seal. Due to this monolithic way of anchorage a bonded system of concrete and metal liner membrane is obtained so that the same deformations of the loading or strain conditions are induced to the very stiff concrete hull as well as to the liner. Because of the complex structural behaviour of the bonded system the evaluation is carried out by the finite element method. The overall system is decoupled in several steps. Due to its considerable stiffness the concrete structure can be regarded as the liner supporting basis. The liner system itself might be subdivided into perfect and imperfect sections discretized by plain or curved elements which are supported by point-wise spring elements representing the stud anchors.

The analysis is performed with a modified ADINA version implicating geometrically and physically non-linear formulations. Typical structural sections are computed by incremental load or strain steps up to or beyond plastification. Because of the substantial computational effort required the number of parameters to be varied is regarded on the basis of Gundremmingen II.

A prior analysis of the boundary moment and support influence permits at first the concentration on a single bi-axially loaded field whose residual parameter variation is checked accordingly to an "assembling matrix". Starting from realistic limit values the variation of one single parameter is terminated if showing linear or pseudo-linear behaviour.

Similar investigations are carried out for uni-axially loaded (imperfect) liner fields as well as for plain liner membrane areas. In a further step those decoupled solutions will be composed to the overall system behaviour. The final solution shall demonstrate - apart from stud anchorage capacity - three typical liner membrane behaviour limits

- limits of elasticity (yielding)
- limits of structural capacity
- limits of tolerable deformations.

1.0 Introduction

The fundamental task of reactor containments consists of public health protection from radionuclide releases. In Germany the BWR Gundremmingen II is the first nuclear power plant with a concrete containment having a thin steel plate liner directly attached by numerous studs to the interior concrete surface to provide an air-tight sealing. Due to this monolithic liner anchorage to the concrete shell a bonded system is obtained which can be subdivided according to its particular functions into the load bearing capacity of the surrounding concrete building and into the gastight sealing of the (very thin) liner membrane. Nevertheless, because of the considerable stiffness differences between concrete hull and liner membrane, the same deformations for the loading or strain conditions from the surrounding building will be transferred by the anchorage elements to the steel plate liner thus inducing here (mostly) unfavorable stress and strain conditions. With regard to the substantial safety features of the liner its constructional design has to include time- and temperature-depending loads as well as accident conditions in order to insure that the liner integrity can be maintained under all circumstances.

2.0 General Structural Behaviour

The overall structural behaviour of the steel plate liner system basically depends on its design criteria - inclusively the potential ways of failure up to the loss of integrity. This results in general in the question in which way the loading conditions induced by external constraints to the membrane structure can be sustained or reduced.

One important structural element represents the stud anchorage system as a suitable stiffness ratio of stud diameter vs. membrane height will decisively influence the general behaviour. If very stiff bolts were provided a deformation constraint might occur directly in the area of the point-wise anchorage which might lead to failure through tearing of the plate. On the other hand stud failure due to shearing caused by very small bolt diameter dimensions must be avoided, too. Analyses in (1) recommend the diameter-height ratio to the factor of 2.0 to obtain conservative structure behaviour; in the case of Gundremmingen II this proportion results in 1.59 (stud diameter 12.7 mm, membrane height 8 mm).

Regarding the liner plate three different phases are imaginable to sustain the loading conditions due to external constraint:

Phase 1 The induced loads or strains are below yielding.(Failure according to the loss of stability shall be excluded which can be guaranteed by a suitable (short) stud distance.)

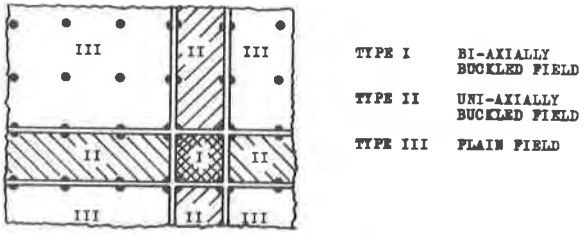
Phase 2 Especially with regard to imperfect (curved) liner fields the induced constraints will lead to stress beyond yielding. In this case the maximum "post-buckling-load" will depend on geometrical as well as material factors.

Phase 3 Due to the rotational capability of plastified zones within a "buckled liner field" additional deformations can be transferred without any stresses until the limit of tolerable strains will be reached, then cracking will lead to the loss of integrity.

3.0 Assumed Failure Modes and Models

Because of short stud distances the "ideal" buckling stresses are beyond yielding so that generally problems of stability can be neglected. Therefore three different liner membrane areas are regarded (s.fig.1) with two failure mechanisms assumed for the imperfect liner fields according to uni- and bi-axial loading conditions. The complex structural behaviour of the bonded system is evaluated by the finite element method. The overall system is decoupled into several steps. Due to its considerable stiffness the concrete structure can be regarded as the liner supporting basis. In order to perform the analysis up to phase 3 it is necessary to reduce the considerable computational effort to a minimum. Therefore the liner system itself is approximately subdivided (s.fig.1). The imperfect (predeflected) fields (type I and II) are discretized by three-dimensional isoparametric 20-node-elements and the perfect (plain) areas of the type III by two-dimensional isometric 4-node-elements. The point-wise supports of the stud anchors are modeled by 2-node-TRUSS-elements.

In a first step the different types are computed separately from each other to set up typical stress-strain-relations.



		
TRUSS-EL.	4-NODE-PLAIN-EL.	20-NODE-CUBIC-EL.
STUD ANCHOR	TYPE III	TYPE I / II
-	TOTAL LAGRANGE	TOTAL LAGRANGE
CURVE DESCR. MODEL	IDEAL ELASTIC-PLASTIC V. MISES CRITERION	IDEAL ELASTIC-PLASTIC V. MISES CRITERION

Fig. 1 Assumed Failure Modes and Models

4.0 Program

The analyses are performed with a modified ADINA version implicating geometrically (Total Lagrange) as well as physically (curved description or ideal elastic-plastic model) non-linear formulations (s.fig.1). The influences of plastification are taken into account by the v. Mises yield criterion. The realization is carried out by a modified Newton-Raphson iteration, i.e. by step-wise incremental linearizations.

With regard to the imperfect liner fields the fundamental difficulty of the computation consists of a suitable preestimation of the incremental load steps which must be carefully handled in the potential failure area as considerable increases of deformations are opposed to very small load increments. To reduce the computational effort as much as possible a semi-automatic load incrementation during operation is developed. By continuous file protection of former results the application of RESTART jobs permits a direct load increment adaptation due to the way of approach to system failure so that the deformations and strains of the post-buckling phase can very accurately be determined (s.fig.2).

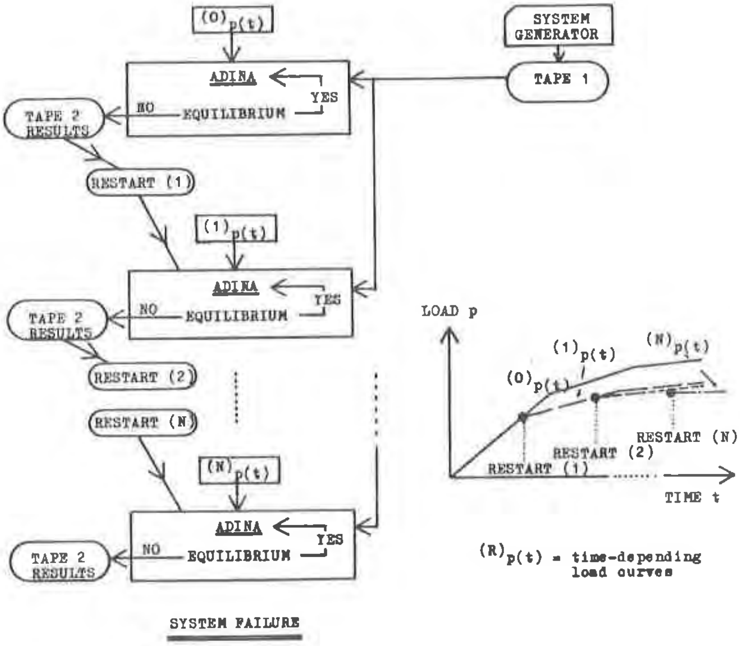


Fig. 2 Semi-Automatic Load Incrementation

5.0 Kinematic Behaviour

During phase 3 only kinematic deformations of the buckled liner fields will be observed. With n being the final step to obtain the post-buckling load limit and the corresponding deformation state it is assumed to have affinity between the real kinematic and the final (n-1, n step) incrementation displacements so that the maximum phase 3 deformations of a buckled field can be estimated to

$$\delta = \delta_n + \alpha \cdot \Delta_{n,n-1} \qquad (1)$$

with $\Delta_{n,n-1} = \delta_n - \delta_{n-1}$ and the corresponding as well as the maximum permissible strains

$$\varepsilon^{perm.}_{max.} = \varepsilon_n + \alpha \cdot \Delta\varepsilon_{n,n-1} \qquad (2)$$

then the total deformation will result in

$$\delta = \delta_n + \frac{\varepsilon^{perm.}_{max.} - \varepsilon_n}{\varepsilon_n - \varepsilon_{n-1}} \left[\delta_n - \delta_{n-1}\right] \qquad (3)$$

6.0 Parametric Investigations

In general a liner behaviour analysis is based on the actual system parameters which might be subdivided into

-	geometry	with	membrane size, imperfections, stud distance and stud anchorage pattern,
-	material	with	steel quality and yield criteria,
-	boundary conditions	with	membrane as well as stud anchorage support,
-	loading conditions	with	direct loads as well as induced strains.

To reduce the number of computations it is necessary to limitate the number of parameters to be varied. On the basis of Gundremmingen II these factors are kept fixed depending on a membrane height of 8 mm, a stud distance of 100/100 mm with quadratic pattern and a ductile steel St 37 with a yield stress approximately 260 N/mm^2. The influence of the residual parameter variation is compared in a tabular summary called "assembling matrix". Starting from realistic limit values the variation of one single parameter is terminated if showing linear or pseudo-linear behaviour or neglegible values.

6.1 Type I and II

With regard to the anchorage stiffness the computations demonstrate that relatively weak stud anchors only give 5% increased load bearing contribution if its own stiffness were augmented up to 50%, whereas large initial bolt stiffness totally reverses the common structural behaviour. Different stud anchorage rigidities are compared in accordance with (1,2,3).

If suitable stud-membrane stiffness ratios are chosen the investigations demonstrate that different functional imperfections (f.e. sine- or cosinecurves) are almost irrelevant in relation to the final post-buckling load. The influence of the mid-predeflection up to approximately 30% of the membrane height is to be pseudo-linear.

To control adjacent membrane effects elastic boundary supports are compared with a free edge behaviour; the evaluation presents 5% conservative influence only so that the consideration of the post-buckling loads of separated single liner fields is demonstrated to be permissible.

Furthermore a convergence check is performed with regard to the results obtained from different finite element discretization always taking advantage of axis symmetric structural behaviour. The number of elements is varied in plain view from 9 to 36 and also in view of the membrane height from 1 to 3 cubic elements, always keeping up the same length to height element ratios. An augmentation from 250 to 1400 degrees of freedom results in a 1,7% difference only (s.fig.3).

6.2 Type III

According to their relative stiffness the plain areas can be regarded as the load bearing liner fields. Different continuous fields are analized by the number of supports and boundary conditions are varied and the obtained stress-strain-curves compared. Conservative loading influences - f.e. frictional and transversal loads directed opposite the buckling failure mechanism - are neglected. The loading cases are substituted to easily comparable strain inducing constrained loads.

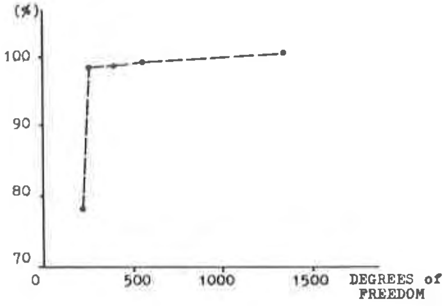


Fig. 3 Convergence Control

7.0 Example

The liner field behaviour in relation to different imperfections is investigated for type I (s.fig.4) as well as for type II (s.fig.5).

In fig.6 load-displacement curves are presented according to stud anchor stiffness values given in (1,2,3).

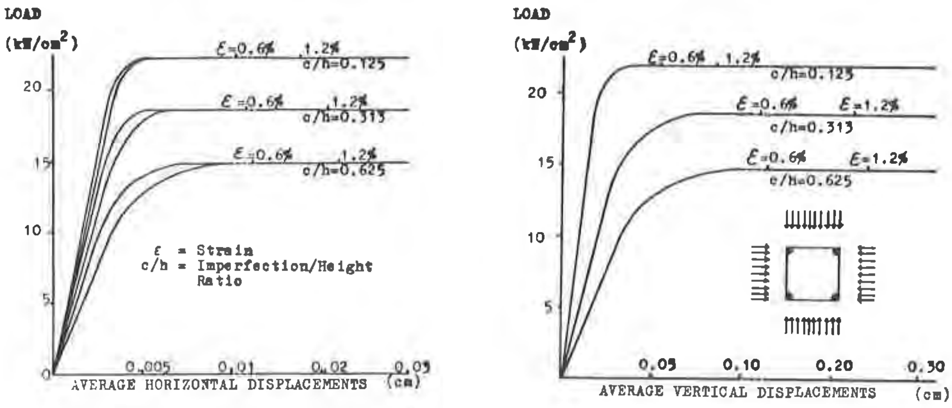


Fig. 4 Type I Load-Displacement Relations

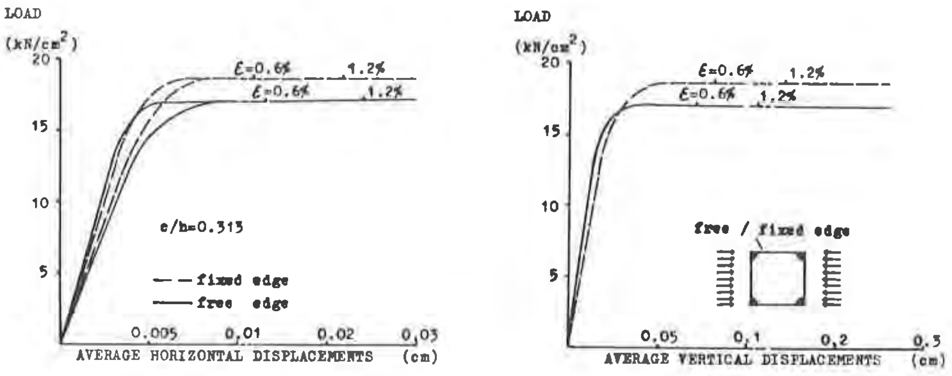


Fig. 5 Type II Load-Displacement Relations

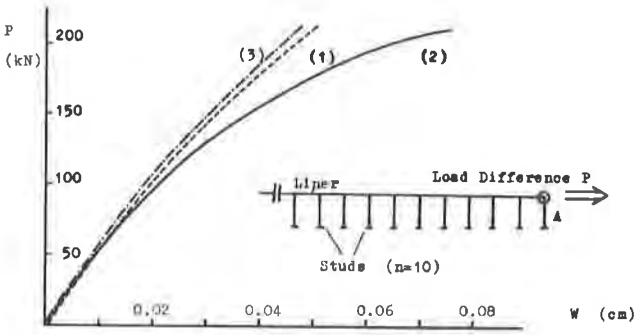


Fig. 6 Type III Point "A" Load-Displacement Relations
due to Stud Anchor Stiffness Values in (1,2,3)

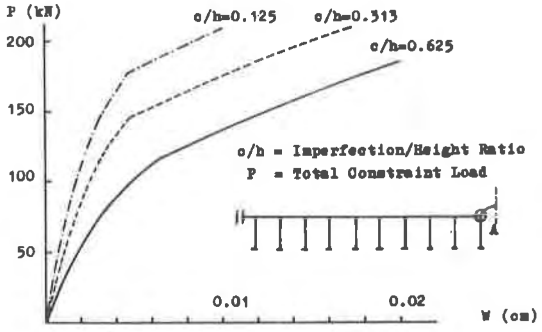


Fig.7 Overall System Behaviour at Point "A"

Finally the decoupled system is composed to estimate the overall system behaviour due to induced constraint loads.

The solutions are summarized in easily understandable diagrams to demonstrate the failure mechanisms (s.fig.7). The investigations are still current.

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