DESIGN STUDY OF REINFORCED AND PRESTRESSED CONCRETE CONTAINMENT VESSELS

R. Meiswinkel¹, A. Garg², H. Hansen², C. Lang³
¹E.ON Kernkraft GmbH, Hannover, GERMANY
²HOCHTIEF Consult IKS Energy, Frankfurt/Main, GERMANY
³IBB Dr.-Ing. Christian Lang Consulting Engineers GmbH, Frankenthal, GERMANY
E-mail of corresponding author: ruediger.meiswinkel@eon.com

ABSTRACT

Various types of containment vessels can be carried out to fulfill the high demands on a safe confinement of fission products. Beside steel containment vessels composite steel-concrete structures seem to be a preferred building structure. These composite steel-concrete structures will be subdivided into reinforced concrete structures with steel liner and prestressed concrete structures with steel liner.

For the design of composite steel-concrete structures, the German standard DIN 25459 [1] can be applied as an alternative to the ASME-Code [2]. In opposite to the ASME-Code, DIN 25459 [1] gives the chance for the consideration of bond behavior in a consequent manner. Corresponding to DIN 25459 [1], an application study will be presented to demonstrate the essential aspects of the design procedure and the structural behavior of steel-concrete containment vessels. This application study demonstrates different structural behavior phenomena of the composite structure and in addition the consequences of the design requirements of DIN 25459.

INTRODUCTION

Regarding safety criteria for nuclear power plants, the safe inclusion of radioactive fission products has to be guaranteed. Therefore, different safety barriers are provided. One of them represents the containment vessel. Such a containment vessel has to be designed especially for accident actions like high internal pressures and high temperatures which result from postulated pipe rupture scenarios.

A valid containment type also frequently used for new developed reactor types is given by a composite steel-concrete structure with the following two components: a reinforced or prestressed concrete structure and a steel liner. The action effects on each component depend on stiffness relationship between the concrete structure and the steel liner. In order to avoid expensive analytical models including the consideration of both components, frequently simplified models with separation of both components will be applied neglecting the load bearing capacity of the steel liner and consequently the bond behavior.

The consideration of the bond behavior in a realistic manner has been the intention to revise DIN V 25459 [3] and to obtain a “new” DIN 25459 [1]. The other intention has arisen from the requirements of European standards called Eurocodes which have been established in the European countries in recent years (see [4], [5], [6]). These Eurocodes are based on a partial safety concept applicable for all kind of building structures in a common way [4]. Accordingly, each structure has to be verified such as to limit the combination of actions with different partial safety factors by the structural resistance which considers the material strength and their specified material safeties. So, for composite steel-concrete structures this partial safety can be used efficiently.

VARIOUS TYPES OF CONTAINMENT STRUCTURES

Overview

Generally, the containment concept requires a double-wall containment structure. The outer wall protects against external actions and the inner wall, so-called containment vessel, is responsible for the safe inclusion of radioactive fission products. So, containment vessels have to fulfill high demands on leak tightness with regard to an adequate design for internal actions especially for internal accidents like LOCA (loss of coolant accidents).

As an alternative to steel containments nowadays for the inner containments structures of light-water reactors, composite steel-concrete structures will be preferred: prestressed containments with a steel liner and reinforced concrete containments with a steel liner. Exemplary, the EPR-containment and the KERENA-containment of supplier AREVA can be mentioned as typical representatives of these composite steel-concrete structures.
The Pressurized Water Reactor (PWR) EPR as a product of the German / French cooperation is under construction in Finland and France at the moment. As shown in Fig. 1, the EPR is characterized by a double outer-wall construction of the containment building: outer reinforced concrete wall with a thickness of 1.30 m to 1.80 m and an inner prestressed concrete wall with a thickness of 1.00 m to 1.30 m. The inner wall is covered by a steel liner (thickness: 6 mm) and bonded with the prestressed concrete wall mainly by headed studs. Due to the relatively small thickness of 6 mm, the erection of the steel liner requires high demands on the prefabrication of the different liner elements and on the transportation from the prefabrication place to the final wall position (see Fig. 2).

The design of the Boiling Water Reactor (BWR) KERENA has been performed as a result of a strategic partnership between AREVA and E.ON [7]. KERENA represents a further development of the German BWR-construction line 72. In difference to this predecessor reactor type characterized by a prestressed containment structure with a steel liner (thickness: 8 mm), for KERENA a reinforced concrete containment with a relatively thick liner (thickness: 10 mm) is provided (see Fig. 3). Due to the thickness of 10 mm, a high level of prefabrication can be achieved. Furthermore, the liner could also serve as a load-bearing element.

Fig. 1  EPR – containment structure

Fig. 2  EPR – steel liner: transportation and assembly of prefabricated elements (AREVA photo)
For the different composite steel-concrete structures, the load bearing capacities in the ultimate limit states (ULS) have to be verified as well as the leak tightness in the different limit states of serviceability (SLS). In these limit states, the most important actions result from test pressure situations and LOCA. The quantification of the actions due to high inner pressures and high temperatures require an expensive analytical model including the consideration of the bond behavior. On the other hand, by neglecting the bond behavior additional design considerations become necessary which have to be justified.

**Design Concept of DIN 25459**


Based on ASME-Code, the German standard DIN V 25459 [3] has been developed for the design of composite steel-concrete containment vessels. Due to the establishment of Eurocodes and due to the request for consequent consideration of the bond behavior, a new revision of DIN 25459 [1] is currently being elaborated starting in the year 2008. In the revised DIN 25459 [1], the partial safety factor concept of the Eurocodes will be considered in compliance with the verification concepts of DIN 25449 [8].

With regard to structural safety including load bearing capacity, different ultimate limit states have to be checked by

$$E_d \leq R_d = R \{f_{k,i} / \gamma_{M,i}\}$$

(1)

$E_d$ represents the design value of action effects resulting from different combinations of actions which will be subdivided in “permanent and temporary design situations” and “accidental design situations” considering different actions, partial safety load factors and load combination factors [8]. The permanent and temporary design situations refer to normal operation phase. The accidental design situations consider extraordinary actions as LOCA or seismic actions.

$R_d$ represents the design values of the structural resistance regarding the different material strength $f_{k,i}$ and partial safety factor $\gamma_{M,i}$. For the different materials - concrete, reinforcement, prestressed steel, steel and studs, partial safety factors $\gamma_{M,i}$ are defined depending on three requirements A1, A2 and A3:

- **A1**: combinations of actions which rank among permanent and temporary design situations of EN 1990 [4]
- **A2**: combinations of accidental actions with a repeated occurrence during service life
A3: combinations of accidental actions with a minor probability of occurrence (≤ 10^-4 /a; actions with single occurrence during the service life). Ensuring the serviceability – especially leak tightness or prestressing demands, the serviceability limit states have to be checked by

$$E_d \leq C_d$$  \hspace{1cm} (2)

where $E_d$ represents the design value of action effects (e.g. stress or crack width) resulting from specified design situations and $C_d$ represents the design value of the serviceability criterion (e.g. permitted stress or permitted crack width).

APPLICATION STUDY: REINFORCED CONCRETE CONTAINMENT

Preliminary Remarks

Considering the design concept of DIN 25459 [1], an application study will be presented to demonstrate the essential aspects of the design procedure and the structural behavior of steel-concrete containment vessels. Within the scope of the application study, a reinforced concrete structure with a steel liner (no prestressing) will be investigated first. The reinforced concrete structure is mainly responsible for inner pressure resistance whereas leak tightness shall be guaranteed by steel liner. Nevertheless, the bond behavior between the reinforced concrete containment wall and the steel liner shall be considered.

The containment of a typical pressurized water reactor building which consists of a cylindrical shell, a torus part and a spherical shell geometry will be analyzed for design study purpose (see Fig. 4). For the design of relevant membrane zones of this containment model, analytical solutions for the structural response can be applied. These solutions will be derived for typical containment actions such as inner pressure, temperature or shrinkage accounting for the bond behavior between reinforced concrete wall and steel liner. Because of low concrete compressive stresses in the structure, creep effects will be neglected in this study.

Fig. 4  Containment vessel: reinforced concrete structure with steel liner
Based on these solutions, the internal forces, stresses and strains of the composite structure can be analyzed for different load situations like “test pressure” or “LOCA-accident”. Subject to structural response, load combinations according to DIN 25459 [1] have to be verified. Thus, ultimate limit states with differentiation into three design requirement categories A1, A2 and A3 result in necessary reinforcement quantities of the reinforced concrete wall. Limit states of serviceability are necessary to limit crack width and to limit stresses in concrete and steel.

Structural Model

For the cylindrical membrane zone of the containment model as shown in Fig 4, a cylindrical shell - membrane supported - can be used to calculate the structural response. So, Fig. 5 shows the solutions of this cylindrical shell for the ring force n, the strain ε and the radial displacement v regarding the actions inner pressure p, temperature gradient T₀ and shrinkage strain εₚₛ.

Now, these solutions of a cylindrical shell - membrane supported - can be applied for the composite structure of the cylindrical membrane zone composed of reinforced concrete wall, steel liner and the bond forces pᵰ (dowel forces of the studs connecting the liner to the wall). As shown in Fig. 6, the compatibility requirement v = v₀ results in the solution for pᵰ which directly determines the solutions n, ε and v for the reinforced concrete wall and the liner. It becomes obvious, that these solutions directly depend on stiffness relation between the wall and the liner (D_c = E_c ⋅ h and D_l = E_l ⋅ t). One approach is given by a linear stiffness assumption.

![Fig. 5 Cylindrical shell, membrane supported, axisymmetric actions p, T₀, εₚₛ (see [9])](image)

**Design Basis (geometry, loading, design situations)**

In Tab. 1, the data for geometry, loading and design situations are summarized. The geometrical data like radius and thickness of the wall shell and liner shell correspond to Fig. 4. The material values have been assumed according to EN 1992-1-1 [5] and EN 1993-1-1 [6].

The given actions consider test pressure and LOCA situations which are typically for a PWR.

**Design analyses**

Based on the solutions given in Fig. 6, the structural analysis of the cylindrical membrane zone with assumed linear stiffness result in the values of Tab. 2. The load bearing of the wall and the liner are quantified and demonstrate the influence of the bond behavior. Subsequently, the following reinforcement quantities can be determined as required and provided quantities:

<table>
<thead>
<tr>
<th>P_L + T_L + S:</th>
<th>req aₙ = n / f_y = 13397 ⋅ 10⁴ / 500 ⋅ 10⁴</th>
<th>= 267.94 cm²/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>req aₙ = n / f_y = 11116 ⋅ 10⁴ / 500 ⋅ 10⁴</td>
<td>= 222.32 cm²/m</td>
<td></td>
</tr>
<tr>
<td>prov: 6 Ø32, s = 15 cm</td>
<td>6 x 53.62 = 321.72 cm²/m</td>
<td></td>
</tr>
</tbody>
</table>

n₁₁ = n = p ⋅ R
ε₁₁ = ε = p ⋅ R/(E ⋅ h) / (E ⋅ h) + αT ⋅ T₀ ⋅ R + εₚₛ
v = p R²/(E ⋅ h) + αT ⋅ T₀ ⋅ R + εₚₛ

p: internal pressure
T₀: temperature
αT: temperature coefficient
εₚₛ: shrinkage strain
E: modulus of elasticity
ε: stress generating strains
poisson ratio υ will be neglected
Considering the provided reinforcement, the test pressure situation \( P_T \) delivers a crack width \( w_k = 0.23 \text{ mm} \) applying the crack width approach of EN 1992-1-1 [5]. Therefore, the crack width limitation of 0.30 mm is fulfilled. Furthermore, the reinforcement steel stresses result in \( \sigma_s = 409 \text{ MPa} < 0.8 f_y = 400 \text{ MPa} \) and accordingly the required serviceability demand for the test pressure situation \( P_T \) can be guaranteed.

![Cylindrical shell: composite structure: concrete wall / steel liner](image)

**Table 1: Geometry, loading and design situations**

<table>
<thead>
<tr>
<th></th>
<th>Concrete wall</th>
<th>Liner</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_c )</td>
<td>24.00 m</td>
<td></td>
</tr>
<tr>
<td>( h )</td>
<td>1.30 m</td>
<td></td>
</tr>
<tr>
<td>( R_l )</td>
<td>23.35 m</td>
<td></td>
</tr>
<tr>
<td>( t )</td>
<td>0.01 m</td>
<td></td>
</tr>
<tr>
<td>( E_c )</td>
<td>33.00 \times 10^3 MPa</td>
<td></td>
</tr>
<tr>
<td>( f_{ys} )</td>
<td>200 \times 10^3 MPa</td>
<td>500 / 540 MPa</td>
</tr>
<tr>
<td>( \alpha_T )</td>
<td>1.2 \times 10^{-5} K^{-1}</td>
<td></td>
</tr>
<tr>
<td>( f_{ys} )</td>
<td>210 \times 10^3 MPa</td>
<td></td>
</tr>
<tr>
<td>( f_{ys} / f_{us} )</td>
<td>275 / 430 MPa</td>
<td>( \varepsilon_{sh} )</td>
</tr>
</tbody>
</table>

**LOCA:**
- Internal pressure \( P_L \):
  \( p = 450 \text{ kN/m}^2 \)
- Temperature \( T_L \):
  \( T_0 = 120 \text{ K} \)

**Test pressure:**
- First pressure test:
  \( p = 1.1 \times 450 = 495 \approx 500 \text{ kN/m}^2 \)

**Shrinkage**:
- Concrete wall:
  \( \varepsilon_{sh} = -0.25 \times 10^{-3} \)

**ULS-verifications:**
- Requirement category A2:
  \( E \{ P_T \} \leq R (\gamma_c = 1.30, \gamma_l = 1.00, \gamma_T = 1.00) \)
- Requirement category A3:
  \( E \{ P_L + T_L + S \} \leq R (\gamma_c = 1.00, \gamma_s = 1.00, \gamma_T = 1.00) \)

**SLS-verifications:**
- Reinforcement steel stresses:
  \( \sigma_s \{ P_T \} \leq 0.80 f_{ys} \)
- Liner steel stresses:
  \( \sigma_s \{ P_T \} \leq f_{ys} \)
- Crack width:
  \( w_k \{ P_T \} \leq 0.3 \text{ mm} \)
The results of Tab. 2 are based on a linear stiffness assumption but the calculated strains of the wall indicate cracking of the whole cross section. The consideration of a cracked wall by assuming reduced stiffness (stiffness of the reinforcement and a concrete stiffness induced by a tension stiffening factor (TST) of 0.1) result in values of Tab. 3 which are quite different to those of Tab. 2. It will become obvious that the stiffness relationship of the wall and the liner influence the load bearing of a composite steel – concrete structure significantly.

All results have been obtained with the Poisson ratio $\nu_c = \nu_l = 0$. However, for temperature and shrinkage $\nu_l = 0.3$ needs to be considered which leads to stress increase - increase of $n_c$ and $n_l$. This increase can be estimated by factor $1/(1-\nu_l) = 1.43$.

**Table 2 Structural responses (uncracked concrete)**

<table>
<thead>
<tr>
<th></th>
<th>$p_d$ [kN/m²]</th>
<th>$v$ [cm]</th>
<th>$n_c$ [kN/m]</th>
<th>$n_l$ [kN/m]</th>
<th>$\varepsilon_c$ [%]</th>
<th>$\varepsilon_l$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_T$: $p = 500$ kN/m²</td>
<td>476.05</td>
<td>0.62</td>
<td>11116</td>
<td>559</td>
<td>0.26</td>
<td>0.27</td>
</tr>
<tr>
<td>$P_L$: $p = 450$ kN/m²</td>
<td>238.44</td>
<td>0.56</td>
<td>10004</td>
<td>503</td>
<td>0.23</td>
<td>0.24</td>
</tr>
<tr>
<td>$T_L$: $T_0 = 120$ K</td>
<td>123.30</td>
<td>0.16</td>
<td>2879</td>
<td>-2879</td>
<td>0.07</td>
<td>-1.37</td>
</tr>
<tr>
<td>$P_L + T_L$</td>
<td>551.75</td>
<td>0.72</td>
<td>12883</td>
<td>-2376</td>
<td>0.30</td>
<td>-1.13</td>
</tr>
<tr>
<td>$S$: $\varepsilon_{sh} = -0.25 \cdot 10^{-3}$</td>
<td>22.00</td>
<td>-0.57</td>
<td>514</td>
<td>-514</td>
<td>0.01</td>
<td>-0.24</td>
</tr>
<tr>
<td>$P_L + T_L + S$</td>
<td>573.75</td>
<td>0.15</td>
<td>13397</td>
<td>-2890</td>
<td>0.31</td>
<td>-1.38</td>
</tr>
</tbody>
</table>

**Table 3 Structural responses (cracked reinforced concrete with tension stiffening, $a_s = 321.72$ cm²/m)**

<table>
<thead>
<tr>
<th></th>
<th>$p_d$ [kN/m²]</th>
<th>$v$ [cm]</th>
<th>$n_c$ [kN/m]</th>
<th>$n_l$ [kN/m]</th>
<th>$\varepsilon_c$ [%]</th>
<th>$\varepsilon_l$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_T$: $p = 500$ kN/m²</td>
<td>416.23</td>
<td>2.17</td>
<td>9719</td>
<td>1956</td>
<td>0.91</td>
<td>0.93</td>
</tr>
<tr>
<td>$P_L$: $p = 450$ kN/m²</td>
<td>374.60</td>
<td>1.96</td>
<td>8747</td>
<td>1760</td>
<td>0.82</td>
<td>0.84</td>
</tr>
<tr>
<td>$T_L$: $T_0 = 120$ K</td>
<td>107.81</td>
<td>0.56</td>
<td>2517</td>
<td>-2517</td>
<td>0.23</td>
<td>-1.20</td>
</tr>
<tr>
<td>$P_L + T_L$</td>
<td>482.41</td>
<td>2.52</td>
<td>11264</td>
<td>-757</td>
<td>1.05</td>
<td>-0.36</td>
</tr>
<tr>
<td>$S$: $\varepsilon_{sh} = -0.25 \cdot 10^{-3}$</td>
<td>19.24</td>
<td>-0.50</td>
<td>449</td>
<td>-449</td>
<td>0.04</td>
<td>-0.21</td>
</tr>
<tr>
<td>$P_L + T_L + S$</td>
<td>501.65</td>
<td>2.02</td>
<td>11713</td>
<td>-1206</td>
<td>1.09</td>
<td>-0.57</td>
</tr>
</tbody>
</table>

**Comparison with an Alternative Prestressed Concrete Containment**

Regarding a prestressed concrete containment wall with the demand that no tensile stress occurs during LOCA situation ($\sigma_c(P + P_L + T_L + S) = 0$), the values of Tab. 2 can be taken into account. Consequently, prestressing $P$
results in ring forces $n_P = -13397 \text{ kN/m}$ and compressive liner strains $\varepsilon_P = -13397/10004 \cdot 24 \cdot 10^{-3} = -0.32 \cdot 10^{-3}$. Creep effects will increase compressive liner strains $\varepsilon_P$ even more severe. As a consequence, the following aspects seem to be significant:

- Prestressing results in action effects of the steel liner with compressive strains which have to be considered in view of possible buckling failure areas.
- In LOCA situations, the values of the compressive strains rise up to $\varepsilon_l = -0.32 \cdot 10^{-3} - 1.38 \cdot 10^{-3} = -1.70 \cdot 10^{-3}$. So, yield strain $\varepsilon_{yl} = 1.31 \cdot 10^{-3}$ will be exceeded extremely and adequate design verifications with limit strains have to be justified.

CONCLUSION

Containment vessels designed as reinforced concrete structures with steel liner or prestressed concrete structures with steel liner represent preferred building structures to guarantee the safe inclusion of radioactive fission products. These composite steel-concrete structures require adequate analytical models to consider the structural behavior realistically.

Regarding the cylindrical membrane zone of a typical containment vessel composed of a reinforced concrete wall and a steel liner, a simplified analytical model has been applied for the design analyses. In consideration of the bond behavior between the concrete wall and the liner, it becomes obvious that stiffness relationship of the wall and the liner influence the action effects of both structural components significantly. So, a robust design requires adequate stiffness estimation for the determination of the action effects.

Furthermore, the design analyses demonstrate that a containment structure without prestressing is able to fulfill the design requirements of DIN 25459 [1] which corresponds to basic design principles of Eurocodes [4], [5], [6]. Such a reinforced concrete structure with steel liner can be carried out in an advantageous manner to guarantee leak tightness of the containment. In comparison to this containment type, a prestressed concrete structure with a steel liner has been analyzed finally. Therefore, LOCA situations result in high compressive steel liner strains which exceed the yield strain extremely. So, these sensitive action effects require additional design aspects which have to be establish among experts.

REFERENCES