EQUIVALENT CONCRETE STRESS BLOCK FOR NUCLEAR CONTAINMENT DESIGN

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ABSTRACT

Section III, Division 2 of ASME Boiler and Pressure Vessel Code provides a set of allowable stress and strain limits for designing nuclear concrete containments. Different allowable stress and strain limits of concrete and reinforcing steel are provided for service and factored loads. The ASME design method requires calculating stresses and strains of concrete sections for flexural and membrane loads to satisfy the equilibrium conditions and stress-strain relationships of concrete steel and comparing the estimated stresses and strains with the allowable limits. However, the ASME design procedure is complex as it involves calculating the nonlinear concrete stress distribution for factored loads. Other nuclear design code (ACI 349 code) for safety-related concrete structures provides a simple design method by the use of an equivalent rectangular concrete stress block. Past studies demonstrated that the use of the stress block simplifies the calculation yet provides reliable and accurate results for section strengths.

This paper proposes a set of stress block parameters using allowable stress and strain limits in the ASME code. With the proposed set of stress block parameters, the equivalent stress block method can be employed to design nuclear concrete containments for flexure and membrane loads. The proposed equivalent stress block method is examined by comparing with the results of conventional ASME design methodology. The proposed method provides a convenient design tool for concrete containments. It is also possible to use more consistent design procedure between nuclear containments and other nuclear safety-related concrete structures.

INTRODUCTION

Section III, Division 2 of ASME Boiler and Pressure Vessel Code [1] provides allowable stress and strain design method of nuclear concrete containments for axial and flexural loads. Different concrete compressive stress-strain relationships are specified in Section CC-3500 depending on the load categories, which are factored loads and service loads. The concrete compressive stress-strain relationship may be assumed to be a triangle, parabola, or any other shape which resembles actual stress distribution for factored loads and the straight line relationship is specified for service loads.

A generally adopted concrete compressive stress-strain relationship for calculating factored load cases is a modified Hognestad's equation [2] as shown below:

$$f_c = 0.85 f_c' \left\{ \frac{2\varepsilon_c}{0.002} - \left(\frac{\varepsilon_c}{0.002} \right)^2 \right\} \quad \text{where } \varepsilon_c \leq 0.002 \tag{1}$$

Because of the nonlinearity of the concrete stress-strain relationship in Eq. (1), complex calculation procedures are required for calculating design strengths for factored loads in accordance with ASME. As a result, a computer-aided calculation tool becomes essential unless overly-simplified straight line relationship is used. On the other hand, calculating design strengths for service loads is straightforward due to the use of a straight line of concrete stress-strain relationship.

In this paper, an equivalent rectangular concrete stress block method is proposed to calculate flexural and membrane strengths in accordance with ASME requirements for nuclear containments. The proposed method provides a convenient tool to calculate the flexural and membrane strengths by avoiding calculation of the actual concrete compressive stress distribution.

ALLOWABLE STRESS AND STRAIN DESIGN METHOD IN ASME

ASME provides the allowable stress and strain design method for computing axial and flexural strengths of nuclear containments. This is because more direct control of concrete cracks is essential for nuclear containments to maintain a certain degree of leak tightness during abnormal/extreme environmental conditions. ASME provides two design methods for factored and service loads.

Allowable compressive stresses of concrete in ASME are summarized in Table 1. ASME defines design load conditions as follows: (1) factored versus service loads, (2) primary versus primary-plus-secondary loads and (3) membrane plus bending versus membrane only. A Primary load is an internal force/moment which is required to equilibrate applied loads. On the other hand, a secondary load is an internal force/moment that is not required for equilibrating the applied loads. The example of secondary loads is an internal force/moment resulting from creep, shrinkage or thermal strains. The modified Hognestad's equation in Eq. (1) is commonly used for factored load design as it meets the ASME requirement that the maximum allowable stress of $0.85f_c'$ corresponds to a limiting strain of 0.002 (see the note in Table 1). A straight concrete stress-strain relationship is specified for service load design in Section CC-3511.2 of ASME. The concrete tensile strength is neglected.

Table 2 summarizes allowable stresses/strains of reinforcing steel in ASME. The allowable stress of reinforcing steel is $0.9f_y$ for factored loads and $0.5f_y$ for service loads. The allowable strain of reinforcing steel is permitted to exceed $0.9\varepsilon_y$ for a few conditions but not exceed $2\varepsilon_y$ for factored primary loads. No allowable tensile strain of reinforcing steel is provided for factored primary-plus-secondary loads. For service primary-plus-secondary loads, allowable stress of reinforcing steel is permitted to increase by $33^1/_3$% (see Table 2).

Table 1: Allowable compressive stresses of concrete in ASME

		Membrane Plus Bending	Membrane Only
Factored Loads	(1) Primary	$0.75f_c'$	$0.60f_c'$
	(2) Primary Plus Secondary	$0.85f_c'$*	$0.75f_c'$
Service Loads	(3) Primary	$0.45f_c'$	$0.35f_c'$** ($0.30f_c'$)
	(4) Primary Plus Secondary	$0.60f_c'$	$0.45f_c'$

*: The maximum allowable stress of $0.85f_c'$ corresponds to a limiting strain of 0.002 in./in.

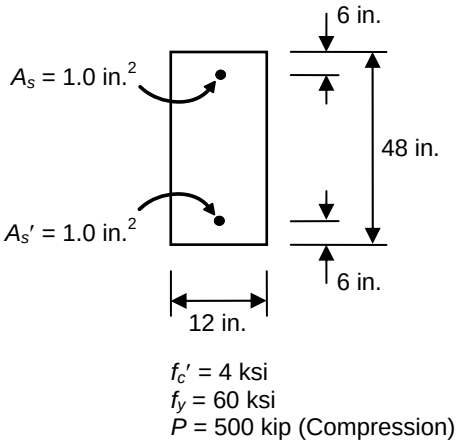
**: At initial prestress

Table 2: Allowable stress/strains of reinforcement in ASME

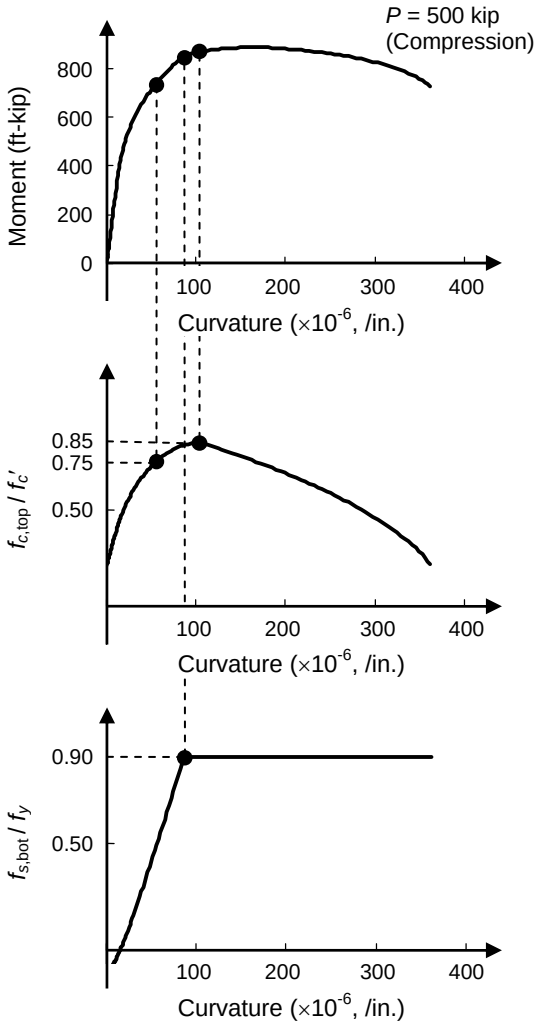
		Membrane Plus Bending	Membrane Only
Factored Loads	(1) Primary	$0.90f_y$ ε_s may exceed $0.9\varepsilon_y$ but not exceed $2\varepsilon_y$.	$0.90f_y$
	(2) Primary Plus Secondary	$0.90f_y$ ε_s may exceed $0.9\varepsilon_y$.	$0.90f_y$
Service Loads	(3) Primary	$0.50f_y$	$0.50f_y$
	(4) Primary Plus Secondary	$0.67f_y$	$0.67f_y$

In order to demonstrate the complexity of calculating design strengths using the ASME method, flexural strengths for factor loads are calculated using a concrete section in Fig. 1(a) for a compressive force of 500 kip. A layer-by-layer analysis was performed to consider the nonlinear concrete stress distribution and the moment-curvature, concrete stress-curvature and reinforcing steel stress-curvature relationships were generated (see Fig. 1(b)). The modified Hognestad's relationship of Eq. (1) was used for this purpose.

The allowable concrete compressive stresses are $0.75f_c'$ and $0.85f_c'$ for primary and primary-plus-secondary loads, respectively. For reinforcing steel, the allowable tensile stress is $0.90f_y$ and yielding is permitted for factored loads. Based on these allowable limits, the flexural strengths of 734 ft-kip and 868 ft-kip are estimated for primary and primary-plus-secondary loads, respectively. Note that the reinforcing steel strain-curvature relationship may be examined if the steel strain governs the design strength. Due to the complexity involved in the calculation, the ASME design method necessities the use of computer programs.



(a) Section details



(b) Section plots

Fig. 1: Calculation of design strength for factored loads in ASME

PROPOSED RECTANGULAR STRESS BLOCK METHOD

An equivalent rectangular stress block method is proposed to simplify the calculation of design strengths of reinforced and/or prestressed nuclear concrete containments. Three parameters are required to use the stress block method: (1) α_1 parameter, which defines an average concrete stress, (2) β_1 parameter to calculate the depth of the equivalent stress block and (3) allowable concrete strain of $\varepsilon_{c,allow}$ to get the strain and stress distributions at the design strength. The role of α_1 and β_1 parameters is illustrated in Fig. 2.

These parameters are derived using the modified Hognestad's relationship of Eq. (1) in the following manner: The first step is to plot the concrete stress distribution (Fig. 3) from a linear strain distribution. The zero-stress is the stress at the neutral axis and the concrete stress $f_{c,allow}$ is the stress at the extreme concrete compression fiber. It is important to note that the concrete stress $f_{c,allow}$ corresponds to allowable concrete stress for membrane and bending as the concrete stress distribution in Fig. 2 can be produced under this condition.

The second step is to find the centroid of the stress distribution, where the concrete compressive force is located (Fig. 3). The location of the concrete compressive force can be expressed as $\beta_1 \cdot c/2$. The β_1 factor was derived by equating the centroid of the concrete stress distribution to $\beta_1 \cdot c/2$. Finally, the α_1 factor was determined by equating the area under the actual stress-strain curve to the area under the rectangular stress block. The whole procedure was repeated by varying the concrete stress $f_{c,allow}$. Allowable concrete strains are derived from Eq. (1) for factored loads and from the straight line relationship with the concrete modulus of E_c for service loads. Different concrete models are used to be consistent with the ASME requirements.

Table 3 summarizes the proposed concrete stress block parameters. In addition, if no prestress is applied, the compressive axial strength of concrete sections shall be limited to the concrete stress of $0.30f_c'$ for service primary load conditions per ASME.

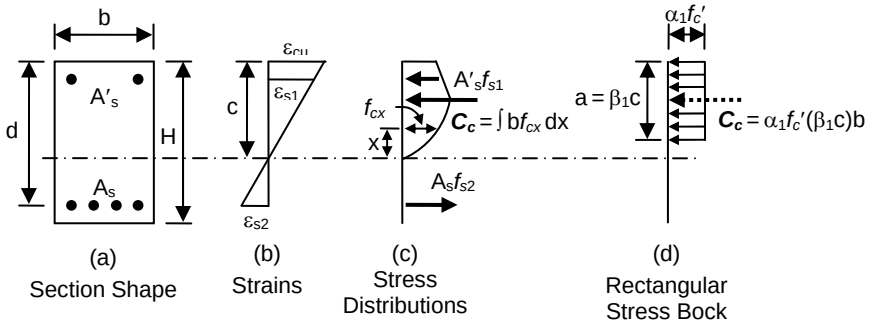


Fig. 2: Rectangular concrete stress block

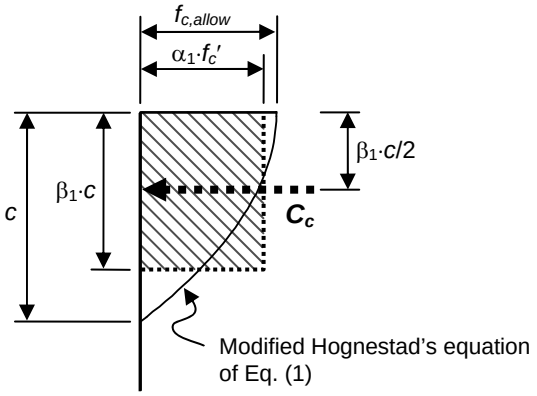


Fig. 3: Derivation of rectangular concrete stress block parameters α_1 and β_1 for ASME

Table 3: Proposed concrete stress block parameters for ASME code

		α_1	β_1	$\varepsilon_{c,allow}$
Factored Loads	(1) Primary	0.60	0.70	0.0013
	(2) Primary Plus Secondary	0.75	0.70	0.0020
Service Loads	(3) Primary	0.35	0.70	$0.45f_c'/E_c$*
	(4) Primary Plus Secondary	0.45	0.70	$0.60f_c'/E_c$*

*: Straight line stress-strain relation is used for service loads to be consistent with ASME code.

P-M INTERACTION CURVES

Using the proposed stress block parameters, a *P-M* interaction curve can be produced in a similar manner of ACI 349 [3] (or ACI 318 [4]). A *P-M* interaction curve and corresponding strain profiles for ASME is shown in Fig. 4. Strain profiles can be categorized to (1) above-balanced, (2) balanced and (3) below-balanced. Tensile stress and strains of reinforcing steel are specified in ASME to be less than the allowable except for factored primary-plus-secondary loads. As a result, the concrete compressive strain in the top fiber is equal to or less than the allowable strain (see Fig. 3(c)). When the reinforcing steel reaches allowable tensile stress and/or strains, the concrete stress in the top fiber decreases from the allowable concrete stress $f_{c,allow}$ to find the force equilibrium condition. The decrease of concrete stress in the top fiber introduces a reduction of the concrete compressive force C_c. Therefore, the decrease of the concrete strain in the top fiber will affect the calculation of the concrete compressive force C_c. Using a linear relation of the decrease of concrete compressive force to the concrete strain in the top fiber, a correction factor $\left(\frac{\varepsilon_{c,top}}{\varepsilon_{c,allow}}\right)$ is also proposed when the concrete strain in the top fiber is less than the allowable concrete strain $\varepsilon_{c,allow}$, as illustrated in Fig. 5. Table 4 illustrates an example of calculating design strengths using the proposed stress block method. The proposed method provides the estimated flexural strength of 832 ft-kip for the section shown in Table 4. Further examples can be found in elsewhere [5].

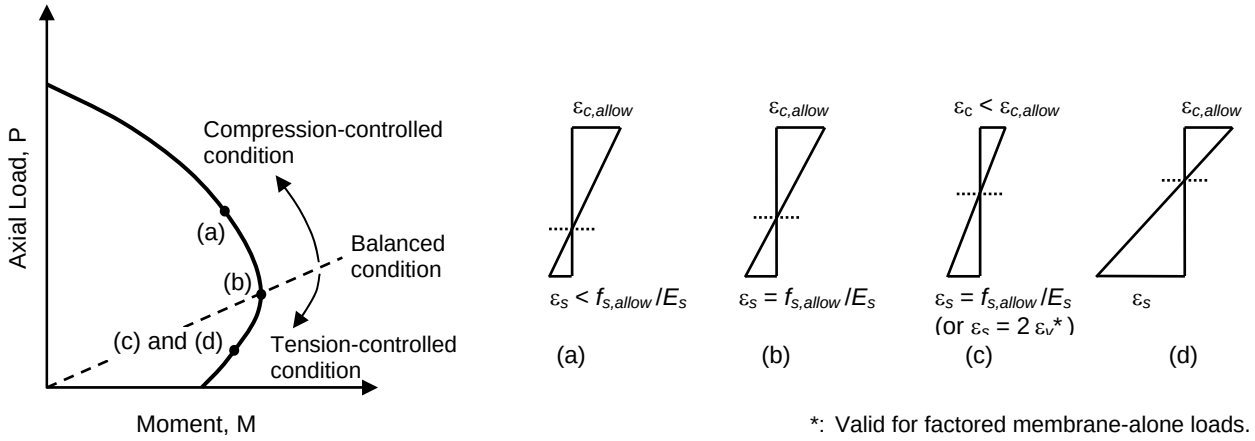


Fig. 4: *P-M* interaction curve and strain profiles of ASME

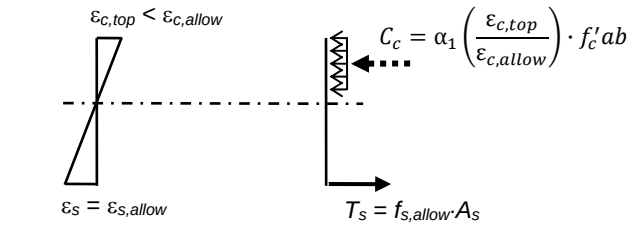


Fig. 5: Correction of concrete compressive force when tensile steel reaches allowable strain

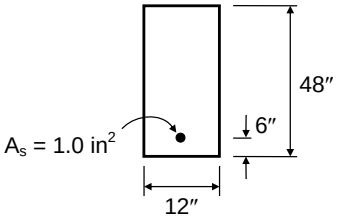
Table 4: Example of calculating design strength using proposed stress block method

Problem statement

Compute the flexural strength of the concrete section for factored primary loads shown below at P = 500 kip).

Solution

The stress block factors and allowable strains are $\alpha_1 = 0.60$; $\beta_1 = 0.70$; $\varepsilon_{c,allow} = 0.0013$; $\varepsilon_{s,allow} = 2\varepsilon_y = 0.00414$ from Tables 2 and 3. Assume the strain condition in Fig. 4(c), where the bottom tensile steel reaches the strain of $2.0\varepsilon_y$. The strain compatibility condition requires



Section details

$$\varepsilon_c = \left(\frac{c}{d-c}\right) \times \varepsilon_{s,allow} = \left(\frac{c}{42\text{ in.} - c}\right)(0.00414)$$

From the force equilibrium of $C_c - T_s = P$,

$$a = \frac{P + (0.9 f_y) A_s}{\alpha_1 \left(\frac{\varepsilon_c}{\varepsilon_{c,allow}}\right) f_c' b} = \beta_1 c$$

$$\frac{500\text{kip} + (0.9 \times 60\text{ksi})(1.0\text{in.}^2)}{(0.60)\left(\frac{\varepsilon_c}{0.0013}\right)(4\text{ksi})(12\text{in.})} = (0.70)c$$

Solving the above two equations gives that a = 10.65 in. and $\varepsilon_c = 0.0023$, which is larger than the allowable concrete strain $\varepsilon_{c,allow} = 0.0013$. Therefore, the assumed strain condition of Fig. 4(c) is invalid.

Assume the stain condition Fig. 4(a) where reinforcing steel does not reach the allowable strain.

$$\varepsilon_s = \left(\frac{d-c}{c}\right) \times \varepsilon_{c,allow} = \left(\frac{42\text{ in.} - c}{c}\right)(0.0013)$$

$$a = \frac{P + (E_s \varepsilon_s) A_s}{\alpha_1 f_c' b} = \beta_1 c$$

$$\frac{500\text{kip} + (29000\text{ksi} \times \varepsilon_s)(1.0\text{in.}^2)}{(0.60)(4\text{ksi})(12\text{in.})} = (0.70)c$$

Table 4: Example of calculating design strength using proposed stress block method (Cont'd)

Solving the above two equations gives that a = 18.17 in., $\varepsilon_c = \varepsilon_{c,allow} = 0.0013$ and $\varepsilon_s = 0.0008 < 0.9\varepsilon_y = 0.00186$.

$$M = (\alpha_1 f_c')ab\left(\frac{h}{2} - \frac{a}{2}\right) - (E_s\varepsilon_s)A_s\left(\frac{h}{2} - d\right) = 832\text{ft·kip}$$

The validity of the proposed stress block method is examined using *P-M* interaction curves for concrete section in Fig. 1(a). Fig. 6 shows a comparison of *P-M* interaction curves from the proposed stress block method and those from the ASME method. ASME method employed the layer-by-layer analysis technique using the concrete curve of Eq. (1) for factored loads and the straight line of Eq. (3) for service loads. The *P-M* interaction curves for service loads based on more realistic concrete relationship of Eq. (4) are also included.

Fig. 6 shows that estimated design strengths of the proposed stress block and ASME methods are in good agreement. The proposed stress block method yielded accurate and conservative predictions for factored loads. For service loads, the proposed stress block method yields slightly larger design strengths than the ASME method around balanced conditions. It is important to note, however, that the ASME method underestimates design strengths because of the use of the straight line concrete relationship.

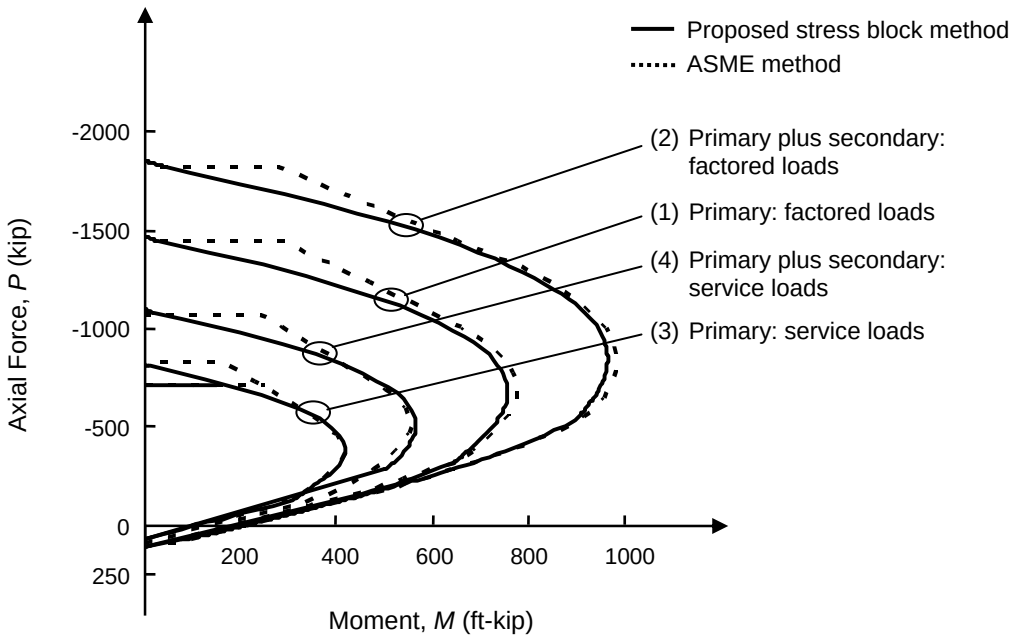


Fig. 6: Comparison between proposed stress block and ASME method

CONCLUSION

A stress block method was developed based on the ASME design requirements. The proposed method provides a simple design method for nuclear containments. Because the calculation of nonlinear concrete stress distribution can be avoided by the use of equivalent stress block, the axial and flexural strengths of nuclear concrete containments can be simplified. The validity of the proposed method was examined using *P-M* interaction curves. The proposed stress block method makes it possible to use a consistent design procedure for both ASME-designed nuclear containments and ACI 349-designed other nuclear safety-related structures. As such, difference will be the use of different stress block parameters. In addition, the proposed stress block method provides a single smooth *P-M* interaction curve, which is applicable to both membrane-only and membrane-plus-bending loads, which further simplifies the design procedures.

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