Seismic capacity design of vertical pressure vessels

N. Shimizu
Iwaki Meisei University, Fukushima, Japan

ABSTRACT: This paper deals with the ultimate strengh seismic design, which we call the seismic capacity design, of tall pressure vessels. Self-standing tall pressure vessels in industrial facilities in Japan are now designed in accordance with the seismic design code based on the elastic analysis rather than the inelastic analysis.

In order to explore a future direction of the seismic design of industrial facilities, the author has tried to make clear the ultimate capacity of pressure vessels during strong ground shakings. The focus of the study is placed on the capacity of anchor bolts. The relationship between the load and ductility factor has been studied by comparing the experimental results and the analysis results when the anchor bolt yielding mechanism is sustained.

1 INTRODUCTION

There are many self-standing tall pressure vessels in industrial facilities like high pressure gas plants. This type of pressure vessel is now being designed in accordance with the Seismic Design Code of High Pressure Gas Facility of the Ministry of Trade and Industry in Japan. The code is established on the basis of the elastic analysis.

On the other hand, Rocommendations for the Seismic Design of Petrochemical Plants by the Ministry of Energy of New Zealand is based on the inelastic analysis which takes the ultimate state of members of structure into account. The design is called seismic capacity design.

This paper investigates the relation of seismic load reduction and ductility on the basis of the philosophy of the capacity design. Experimental study focusing on the anchor bolt yielding has been conducted and the results are compared with the results of the analysis by using Newmark Model. Finally , the seismic load reduction against ductility is discussed from the seismic design load view point.

2 BRIEF DESCRIPTION OF CAPACITY DESIGN

2.1 Seismic load and detail design in capacity design

(i) Seismic load
  (1) design method: strength design
  (2) horizontal seismic force: Seismic load is calculated by,

$$V = C_{H\mu} Z_H W_T \qquad (1)$$

where, $C_{H\mu}$ is the basic horizontal seismic coefficient and Z_H return period coefficient

Ductlity factor μ of vertical pressure vessel is taken as $\mu = 2$.

  (3) distribution of horizontal seismic force: The force is calculated by,

$$F_x = V \ (W_x h_x^k / \Sigma W_x h_x^k) \qquad (2)$$

where, V is caluculated from Eq. (1).
(ii) General principle of capacity design

In the seismic capacity design of the elements of structure shall be so proportioned that a rational yielding hierachy of the primary sturctral system provides an appropriate level of energy dissipation under severe deformation.
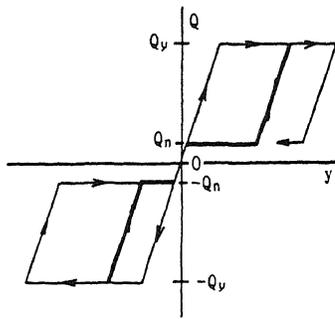
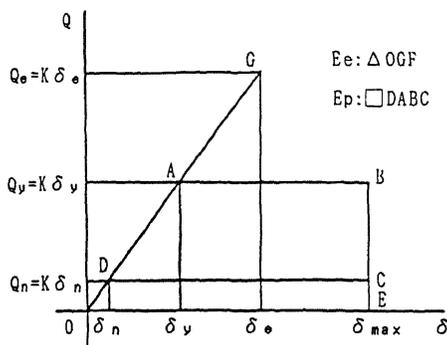Figure 1. Restoring force-displacement curve of vertical vessel

Figure 2. Idealized restoring force-displacement curve of vertical vessel

2.2 Procedure of capacity design for vertical vessel

A brief procedure of the capacity design of vertical vessel is described as follows on the premise that anchor bolts is taken as yielding member.

(1) seismic load (base shear Q_E and overturning moment M_E) is determined by Eqs. (1) and (2).

(2) Anchor bolt considered as the energy dissipating part is designed by Q_E and M_E.

(3) Actual capacity of the anchor bolt is calculated. In this process, increase of strength of yielding part given by the following ① and ② are considered.

① Usually, the actual size of the member is larger than that determined from the required size of the member based on the seismic design load, because the actual member is selected from the standard products. This overstrength factor is denoted by $\phi_G(\geqq 1)$.

② Usually, yield strength of the actual member is larger than that of the nominal strength (for example, in New Zealand,

actual strength $=1.25\times$ nominal strength for steel member). This overstrength factor is denoted by $\phi_H(>1)$.

(4) For un-yielding members, the size is determined from Eq. (3).

$$Q_C = \phi_G \phi_H Q_E, \quad M_C = \phi_G \phi_H M_E. \quad (3)$$

3. RESTORING FORCE CHARACTERISTICS OF VERTICAL VESSELS

Restoring force characteristics of vertical vessels can be given as in Figure 1, when the anchor bolt yielding mechanism is sustained.

Newmark (Veletsos & Newmark 1960) obtained the relationship between the maximum elasto-plastic displacement response δ_{max} for a single-degree-of-freedom system having perfect elasto-plastic restoring force characteristics and the maximum elastic displacement response δ_e for a single-degree-of-freedom linear system having the same slope as that of the initial slope of the perfect elasto-plastic system. That is, the relationship can be written as

$$\delta_{max}/\delta_e = \mu/\sqrt{2\mu-1} \quad (4)$$

where, μ denotes the ductility factor which is defined as the ratio of the maximum displacement response to the yield displacement in the perfect elasto-plastic system, i.e.,

$$\mu = \delta_{max}/\delta_y. \quad (5)$$

In order to apply the concept of Newmark's model to the restoring force characteristics of vertical vessel with anchor-bolt yielding shown in Figure 1, the system is idealized as in Figure 2. In Figure 2, the nomenclatures are defined as

Q_y, δ_y :yield load and displacement due to anchor bolt yielding

Q_n, δ_n :shear force and displacement corresponding to the moment due to vertical load

Q_e, δ_e :responses of maximum elastic load and displacement for elastic system

δ_{max} :response of maximum elasto-plastic displacement

From Figure 2, the relationship between δ_{max} and δ_e will be obtained. The ratio of Q_n and Q_y is defined as

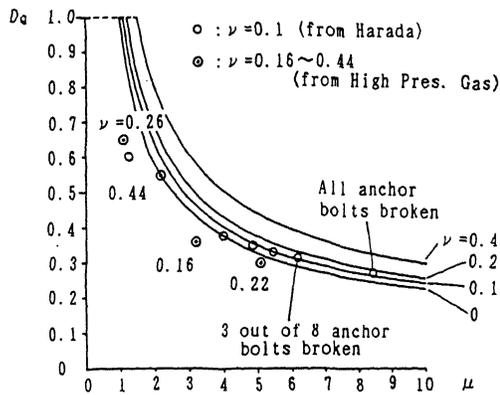$$\nu = Q_n/Q_y = \delta_n/\delta_y. \quad (6)$$

Figure 3. Relationship between load reduction factor D_Q and ducyility factor μ
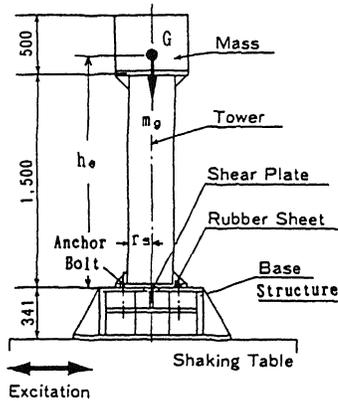

Figure 4. Experimental set-up of tower model for shaking table excitation test
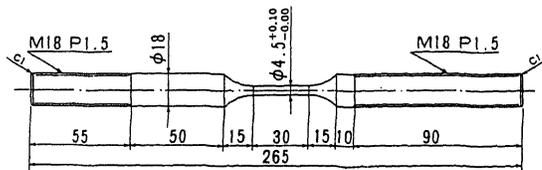

Figure 5. Anchor bolt profile

It is assumed that the strain energy of inelastic response of anchor bolt yielding E_p (area of $\square$DABC) is equal to the strain energy of elastic response E_e (area of $\triangle$OGF) . Since E_p and E_e are described as

$$E_p = (1/2)K\delta_y{}^2(1-\nu)^2+K\delta_y{}^2(1-\nu)(\mu-1)$$
$$E_e = (1/2)K\delta_e{}^2 \qquad (7)$$

then,

$$\delta_e/\delta_y = \sqrt{(1-\nu)(2\mu-1-\nu)} \qquad (8)$$

is obtained under the assumption that $E_p=E_e$. Furthermore, $Q_e/Q_y = \delta_e/\delta_y$, then

$$Q_y = D_Q \cdot Q_e \qquad (9)$$

is obtained. Where,

$$D_Q = 1/\sqrt{(1-\nu)(2\mu-1-\nu)}. \qquad (10)$$

The relation of D_Q and μ is shown by the smooth curve in Figure 3 with respect to ν.

4. EXPERIMENTAL STUDY OF VERTICAL VESSELS

A shaking table excitation test was conducted for evaluating the reduction of seismic design load due to energy absorption of anchor bolt yielding.

Figure 4 is a experimental set-up of the tower model which simulates a tall vertical vessel on a large shaking table.

The model is composed of a tower body, a mass, and a base plate. The base plate welded to the tower body is fixed with eight equally spaced anchor bolts to the base structure which is anchored to the shaking table. The 1,000kg mass is placed on the top of the tower body so that the center of gravity of the tower model locates at 1.60m height from the base plate.

The tower model is designed so as to prevent plastic deformation of the base plate and any other parts of the tower model except for the reduced section of the anchor bolts. A shear plate welded to the bottom of the base plate prevents for tramsmitting the shearing force from the tower body to the anchor bolts. A rubber sheet of 2mm thick is inserted between the base plate of the tower and the base structure.

Figure 5 shows the profile of the anchor bolts. which is made of mild steel(JIS Code S45C). The diameter and the length of the reduced section is 4.5 mm and 30 mm respectively. The initial tightening force on the eight anchor bolts is applied so that strain guages on the reduced section shows one-fifth of the elastic limit(=500$\mu\varepsilon$).

Kinetic energy supplied to the tower model and the dissipation energy absorbed in the yielding anchor bolts will be given as follows. Eq. (11) gives the total amount of energy input E(t) for a single-degree-of-freedom system,

Table 1. Ductility factor μ, load reduction factor D_Q and other values

Test No.	Q_y [kN]	δ_y [cm]	K [kN/cm]	W_e [Nm]	δ_p [mm]	W_p [Nm]	η [-]	ν [-]	W_e' [Nm]	$W_e'+W_p$ [kN/cm]	δ_e [cm]	δ_{max} [cm]	μ [-]	D_Q [-]
021					1.9	147	5.9			16.7	1.30	1.98	4.0	0.38
036					2.3	179	7.2			19.9	1.42	2.42	4.8	0.35
038	9.87	0.5	19.7	25	4.0	313	12.5	0.1	20.3	33.3	1.84	4.22	8.6	0.27
053					2.9	228	9.1			24.8	1.59	3.08	6.2	0.31
055					2.5	201	8.0			22.1	1.50	2.71	5.4	0.33
082					0.6	47	1.9			6.7	0.83	0.63	1.2	0.60
T1-3	239	1.84	130	2200	2.5	3910	1.8	0.26	1200	511	2.81	2.05	1.1	0.65
T1-4	140	1.86	75	1300	5.0	3910	3.0	0.44	410	432	3.39	4.10	2.2	0.55
T4-4	374	1.98	189	3700	7.8	25200	6.8	0.16	2610	2780	5.43	6.40	3.2	0.36
T5-1	276	1.79	154	2480	11.8	25100	10.1	0.22	1510	2660	5.87	9.68	5.4	0.30

note: $\eta = W_p/W_e$, $\nu = Q_n/Q_y$, $W_e' = W_e(1-\nu)^2$, $\delta_e = [2(W_e'+W_p)/K]^{1/2}$, $\delta_{max} = (h_e/r_s)\delta_p$.
$\mu = \delta_{max}/\delta_y$, $D_Q = Q_y/Q_e = \delta_y/\delta_e$, $Q_n = mgr_s/h_e$

$h_e = 160$ cm	for Test No.	$h_e = 489$ cm for Test No.
$r_s = 15$ cm	021 , 036	$r_s = 59.6$ cm T1-3 , T1-4
$m = 1000$ kg	038 , 053	$m = 51570$ kg T4-4 , T5-1
$Q_n = 0.92$ kN	055 , 082 ,	$Q_n = 61.7$ kN

$$E(t) = -M\int_0^t \ddot{x}_\theta(\tau) \cdot \dot{x}_\theta(\tau)\, d\tau \qquad (11)$$

where, M is the mass, $\ddot{x}_\theta$ the input accelera-tion, and $\dot{x}$ relative velocity of the center of gravity of tower with respect to the shaking table. E(t) can be regarded as the sum of the elastic vibration evergy W_e and the plastic strain energy W_p, i.e.,

$$E = W_e + W_p \qquad (12)$$

where,

$$W_e = (1/2)\delta_y Q_y = E_e \qquad (13)$$
$$W_p = 2 \cdot T_y \cdot \delta_p \qquad (14)$$

and δ_p is average ultimate elongation of anchor bolts. T_y, the resultant anchor bolt tensile force, is given by

$$T_y = A \cdot \delta_y \qquad (15)$$

where, A is equivalent total sectional area of anchor bolts. Table 1 lists the values of W_e and W_p and other values for each test.

5. CONSIDERATION ON SEISMIC DESIGN LOAD

D_Q in Fig.3 shows the ratio of the required in-elastic seismic load Q_y and the required elastic seismic design load Q_e. The value D_Q indicating the load reduction factor can be used when in-elastic spectrum is obtained from the elastic response spectrum. Table 1 lists the experimental results of chapter 4 and of the existing study (High Pressure Gas Security Assoc. 1982) (Nomenclatures in Table 1 are refered to Fig.1 and 4).

Experimental results ($\bigcirc$ and $\bigcirc$ mark) are plotted in Figure 3 together with the theoretical curves of Eq.(10). For μ equal to $4\sim9$, D_Q of the experimental results and of the theoretical results show considerably good agreement, whereas for $\mu \lesssim 4$, they do conincide well with each other.

6. CONCLUDING REMARK

Capacity of anchor bolts for vertical vessel when the anchor bolt yelding mechanism is sustained has been studied by theoretical and experimental ways. From this study, seismic load reduction factor D_Q has been theoretically and experimantally determined against the ductility factor μ for the ratio ν (=Q_n/Q_y), and it has been found that D_Q given by Eq.(10) can be used for the determining the seismic design load of vertical vessels when the capacity design will be undertaken.

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