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Dynamic Analysis of Reinforced Concrete Walls Subjected to Blast Loading

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1. Introduction

Improvised explosive devices (IEDs) deployed in a variety of ways have been used by terrorists to cause loss of life and property damage in both military and civilian environments [1]. Because the components and instructions to produce the IEDs are highly accessible, such threats using the IEDs are expected to increase. In this aspect, nuclear facilities are no exception.

For malicious purposes, the IEDs could be abused to destruct the storage for radioactive materials in nuclear facilities, and consequently induce radiation releases. To limit the terrorist attacks using explosives, the storage walls must be sufficiently resistant to the impact of explosives.

In this study, the dynamic analysis of reinforced concrete (RC) walls subjected to blast loading were conducted to evaluate the variation in deformation depending on wall thickness, diameter of reinforcing bar (rebar), and reinforcement ratio. Previous studies were referred to make use of the blast loads generated by the detonation of trinitrotoluene (TNT) at ground surface; and the dimensions, reinforcement details, and material properties of the RC walls containing radioactive materials in nuclear facilities [2, 3]. For the dynamic analysis, the experimental data provided by "Structure to Resist the Effects of Accidental Explosions" (UFC 3-340-02) were used [4].

The results showed that the explosion resistance of the RC walls strengthens with increasing wall thickness, rebar diameter, and reinforcement ratio. Furthermore, the deformation of a RC wall was significantly reduced when a TNT charge was detonated at a distance of more than 3 m. Therefore, except for making the RC wall with excellent explosion resistance, blocking explosive detonation in close proximity of a RC wall can play an important role in the preservation of the RC wall.

2. Methods and Results

2.1 Description of blast-loading environment

As shown in Fig. 1, the blast wave generated by hemispherical TNT surface burst was assumed to be perpendicularly propagated to the 3×3 m RC wall.

Figs. 2 and 3 present the peak reflected pressures and load durations with the TNT charge weights of 3—30 kg and the standoff distances of 0.5—10 m referred in the previous study [2]. The values of blast loads were used for the dynamic analysis of RC walls.

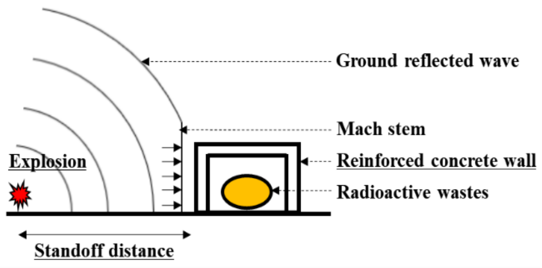

Fig. 1. Description of surface burst blast environment [2].

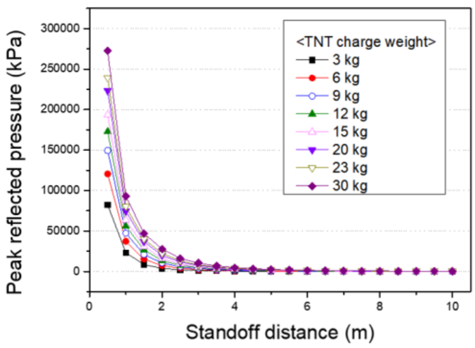

Fig. 2. Peak reflected pressures with the TNT charge weights of 3—30 kg as a function of standoff distance [2].

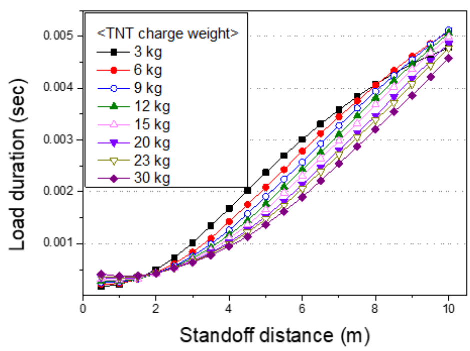

Fig. 3. Load durations with the TNT charge weights of 3—30 kg as a function of standoff distance [2].

2.2 Structural features of reinforced concrete walls

In the previous study, the dimensions, reinforcement details, and material properties of the RC walls containing radioactive materials in nuclear facilities were examined [3]. These data were used to identify the variation in deformation depending on wall thickness, diameter of rebar, and reinforcement ratio.

As assumed in the previous study, the RC walls were considered to have the same area as the 3×3 m (Length (L)×Height (H)) in the direction of a blast wave, whereas wall thickness (D_t) is varied depending on case. As illustrated in Fig. 4, horizontal and vertical rebars were concerned to be symmetrically placed upward and downward. Lacings and stirrups were not considered.

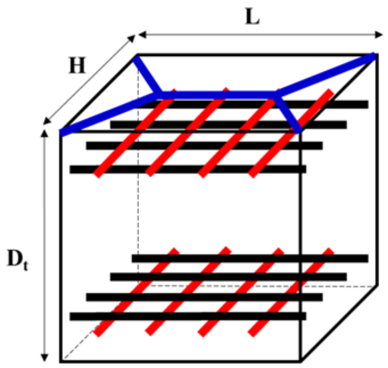

Fig. 4. Schematic drawing of reinforced concrete wall (Black line : horizontal rebar, Red line : vertical rebar, and Blue line : yield line locations).

In this study, as summarized in Table I, the four cases were analyzed, respectively.

Table I: The dimensions, reinforcement details, and material properties of reinforced concrete walls examined [3].

Properties	Unit	Case number			
		1	2	3	4
Length (L)	m	3	3	3	3
Height (H)	m	3	3	3	3
Wall thickness (D_t)	m	0.3	0.2	0.3	0.3
Cover thickness (D_{cov})	mm	20	20	20	20
Diameter of horizontal reinforcement (D_{hor})	mm	15.9	15.9	19.1	15.9
Diameter of vertical reinforcement (D_{ver})	mm	12.7	12.7	25.4	15.9
Ratio of horizontal reinforcement (ρ_{hor})	-	0.005	0.008	0.01	0.004
Ratio of vertical reinforcement (ρ_{ver})	-	0.003	0.005	0.017	0.004
Density of steel (ρ_s)	10^3 kg/m^3	7.854	7.854	7.854	7.855
The modulus of elasticity of reinforcing steel (E_s)	10^{11} Pa	1.999	1.999	1.999	1.999
Yield stress of reinforcing bar (f_y)	10^8 Pa	4	4	4	4.137
Density of concrete (ρ_c)	10^3 kg/m^3	2.403	2.403	2.403	2.403
The modulus of elasticity of concrete (E_c)	10^{10} Pa	2.616	2.616	2.757	2.664
Compressive strength of concrete (f'_c)	10^7 Pa	2.7	2.7	3	2.8

Case #1, #2 : The spacing of horizontal and vertical rebars is identical.

2.3 Assumptions for dynamic analysis

UFC 3-340-02 provides the process of deriving the dynamic strength and design of slabs, beams, and columns. Because the TNT charges were assumed to be detonated towards the RC walls, the slab constituting ceilings or floors were not considered. For columns, the blast loads are transmitted through slabs and beams, and these members filter the dynamic effect of a blast loading. However, beams are primary support members not to attain large plastic deformations [4]. For conservative analysis, the RC walls were concerned as the RC beams.

Crushing of the concrete cover over the compression reinforcement is not exhibited in elements with support rotations less than 2 degrees. As explained in Section 2.6, because the deformation criteria for support rotation was set to be less than 2 degrees, the RC walls were assumed to have the cross-section type I with no crushing or spalling [4].

When it comes to yield line locations, as presented in Fig. 5(a), the pattern of symmetrical yield lines was assumed to be developed on the RC walls through the process of first, second, and final yields because the blast loads were formerly assumed to be delivered uniformly on the RC walls. First, second, and final yields are represented in Figs. 5(b) —(d), respectively.

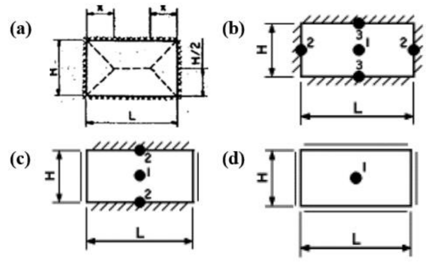

Fig. 5. (a) Symmetrical yield line locations for two-way element with four edges supported; and uniformly-loaded two-way elements with (b) all edges fixed, (c) two opposite edges fixed and two edges simply-supported, and (d) four edges supported [4].

2.4 Input parameters for utilization of UFC 3-340-02

For utilization of UFC 3-340-02, the values of the dimensions and reinforcement details of the RC walls were converted into the values of input parameters as described in Fig. 6 and Table II.

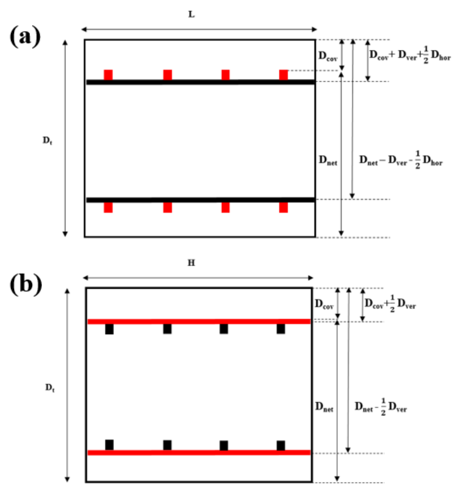

Fig. 6. Reinforced concrete cross-sections: (a) horizontal direction, and (b) vertical direction.

Table II: The input parameters derived from the dimensions and reinforcement details of reinforced concrete walls.

Input parameters	**Related equations**
Ratio of element length to height (L/H)	L/H = 1
Net section thickness (D_{net})	$D_{net} = D_t - D_{cov}$
Horizontal distance from compression fiber to centroid of compression reinforcement (D'_h)	$D'_h = D_{cov} + D_{ver} + D_{hor}/2$
Vertical distance from compression fiber to centroid of compression reinforcement (D'_v)	$D'_v = D_{cov} + D_{ver}/2$
Horizontal distance from compression fiber to centroid of tension reinforcement (D_h)	$D_h = D_{net} - D_{ver} - D_{hor}/2$
Vertical distance from compression fiber to centroid of tension reinforcement (D_v)	$D_v = D_{net} - D_{ver}/2$

Likewise, the values of input parameters were determined from the material properties of the RC walls and the general values provided by UFC 3-340-02, as summarized in Table III.

Table III: The input parameters derived from the material properties of reinforced concrete walls and UFC 3-340-02.

Input parameters	**Related equations**
Dynamic increase factor for rebar (DIF_s)	$DIF_s = 1.17$
Dynamic design stress of rebar (f_{ds})	$f_{ds} = f_y \times DIF_s$
Dynamic increase factor for concrete (DIF_c)	$DIF_c = 1.19$
Dynamic design stress of concrete (f_{dc})	$f_{dc} = f'_c \times DIF_c$
Dynamic increase factor for shear (DIF_{sh})	$DIF_{sh} = 1.1$
Dynamic design stress for shear (f_{dsh})	$f_{sh} = f'_c \times DIF_{sh}$
Poisson's ratio (v)	v = 0.167

2.5 Dynamic analysis of reinforced concrete walls

Based on the values of the abovementioned input parameters, the properties of first, second, and final yields occurring in the RC walls were calculated by using the experimental data and equations given in UFC 3-340-02. According to the calculation procedures indicated in the document, the values of dynamic design factors such as ultimate resistance (R_u), equivalent maximum elastic deflection (X_E), equivalent elastic stiffness (K_E), and effective natural period of vibration (T_n) were defined.

With the values of dynamic design factors, an acceleration-impulse extrapolation numerical method was used to derive the maximum deflection (X_m) induced by blast loads as presented in Fig. 7 [4].

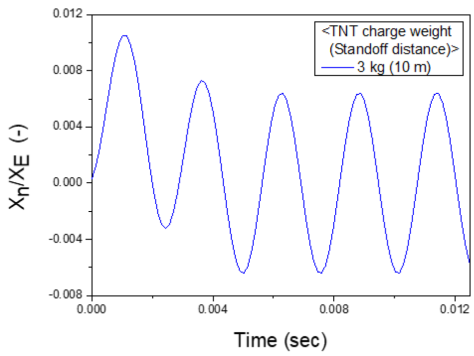

Fig. 7. An example of the deflection prediction in a RC wall using an acceleration-impulse extrapolation numerical method (X_n : deflection depending on time step).

Then, the maximum support rotation (θ_m) in units of degrees was defined according to equation (1) [4].

$$\theta_m = \frac{X_m}{X_E} \tag{1}$$

The θ_m was used as the indicator of deformation criteria for RC walls.

2.6 Deformation criteria for reinforced concrete walls

According to UFC 3-340-02, the protection afforded by a facility or its components are subdivided into four protection categories. Especially, protection category 1 is the highest level which protects personnel against the uncontrolled release of active radiological materials and equipment from blast pressures. In the same principle, the possibility of radiation releases from inside the RC walls could be reduced.

Therefore, the deformation criteria of protection category 1 ($\theta_m \leq 2$) was used for dynamic analysis.

3. Results and discussion

Figs. 8—11 show that support rotation tends to increase as either the standoff distance decreases or the TNT charge weight increases. Moreover, it was confirmed that the support rotations of cases #1—4 decrease to less than 2 degrees when the 30 kg TNT charge is detonated at a distance of more than 3 m.

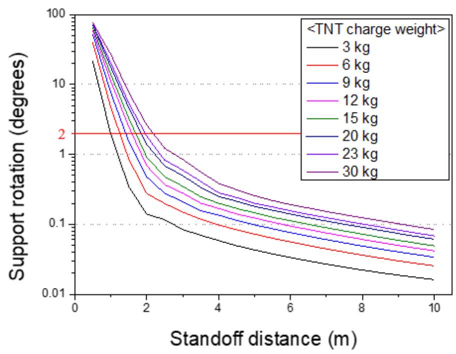

Fig. 8. Support rotations of case #1 with the TNT charge weights of 3—30 kg as a function of standoff distance.

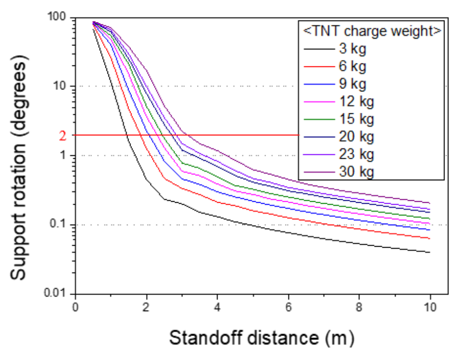

Fig. 9. Support rotations of case #2 with the TNT charge weights of 3—30 kg as a function of standoff distance.

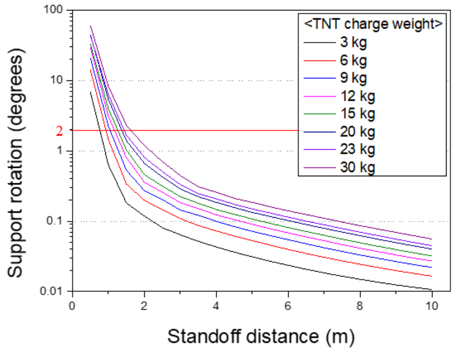

Fig. 10. Support rotations of case #3 with the TNT charge weights of 3—30 kg as a function of standoff distance.

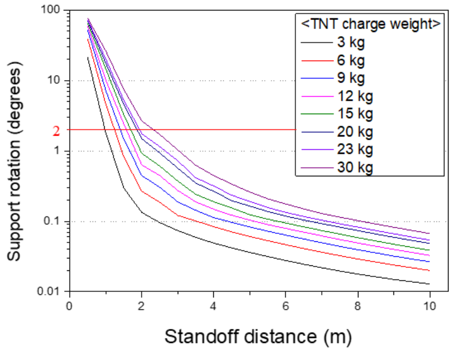

Fig. 11. Support rotations of case #4 with the TNT charge weights of 3—30 kg as a function of standoff distance.

As presented in Figs. 8 and 9, even though the cases #1 and #2 have the same diameter and spacing of horizontal and vertical rebars, the support rotation of case #1 is smaller than that of case #2. Considering that the wall thickness of case #1 (D_t=0.3 m) is thicker than that of case #2 (D_t=0.2 m), the result implies that a thick RC wall has better explosion resistance.

Figs. 10 and 11 describe that the support rotation of case #3 is smaller than that of case #4, whereas the cases #3 and #4 have the same wall thickness. The diameter of the horizontal and vertical rebars for case #3 (D_{hor}=19.1 mm, D_{ver}=25.4 mm) is larger than that for case #4 (D_{hor}=15.9 mm, D_{ver}=15.9 mm), and the reinforcement ratio for case #3 (p_{hor}=0.01, p_{ver}=0.017) is greater than that for case #4 (p_{hor}=0.004, p_{ver}=0.004). Thus, it represents that a large-diameter of rebars with a high reinforcement ratio strengthens explosion resistance.

4. Conclusion

In this study, the dynamic analysis of RC walls subjected to blast loads generated by TNT charges were conducted to identify the variation in deformation depending on wall thickness, diameter of rebars, and reinforcement ratio. The RC walls containing radioactive materials in nuclear facilities were subject to the dynamic analysis. The dimensions, reinforcement details, and material properties of the RC walls were examined and used to calculate the maximum support rotation expected by blast loads. The equations and experimental data provided by UFC 3-340-02 were utilized for dynamic analysis.

The analysis results showed that the explosion resistance of the RC walls increases with increasing wall thickness, rebar diameter, and reinforcement ratio. Moreover, the deformation of the RC walls decreases as the standoff distance of the TNT charges increases, especially at a stand distance of more than 3 m. Therefore, as much as building the RC walls with excellent explosion resistance, blocking the explosive detonation close to the RC walls can be an effective way of preventing deformation.

ACKNOWLEDGEMENT

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REFERENCES

[1] National Academies of Sciences, Engineering, and Medicine, “Reducing the Threat of Improvised Explosive Device Attacks by Restricting Access to Explosive Precursor Chemicals”, The National Academies Press, Washington, DC 2018.
[2] W. Kim, S. Yu, J. Cha, “Blast Load Assessment on a Reinforced Concrete Wall”, Korean Radioactive Waste Society, 2021 Fall Academic Conference, Dec.9-11, 2020.
[3] Korea Institute of Nuclear Nonproliferation and Control, “Performance Data Verification of Protection Facilities against Explosives”, KINAC/CR-004/2016, 2016.
[4] U.S. Department of Defense, “Structures to Resist the Effects of Accidental Explosions”, UFC 3-340-02, 2008.