Structural Engineering and Mechanics, Vol. 9, No. 3 (2000) 305-321
DOI: http://dx.doi.org/10.12989/sem.2000.9.3.305

Simplified slab design approach for parking garages with equivalent vehicle load factors

Hyo-Gyoung Kwak† and Jong-Young Song‡

Department of Civil Engineering, Korea Advanced Institute of Science and Technology, 373-1 Kusung-Tong, Yusung-ku, Taejon 305-701, Korea

Abstract. This paper develops a simplified, but effective, algorithm in obtaining critical slab design moments for parking garages. Maintaining the uniformly distributed load concept generally adopted in the design of building structures, this paper also introduces the equivalent vehicle load factors, which can simulate the vehicle load effects without taking additional sophisticated numerical analyses. After choosing a standard design vehicle of 2.4 tons through the investigation of small to medium vehicles made in Korea, finite element analyses for concentrated wheel loads were conducted by referring to the influence surfaces. Based on the obtained member forces, we determined the equivalent vehicle load factors for slabs, which represent the ratios for forces under vehicle loads to those under uniformly distributed loads. In addition, the relationships between the equivalent vehicle load factors and sectional dimensions were also established by regression, and then used to obtain the proper design moments by vehicle loads. The member forces calculated by the proposed method are compared with the results of four different approaches mentioned in current design codes, with the objective to establish the relative efficiencies of the proposed method.

Key words: parking garage; vehicle loads; distributed loads; equivalent vehicle load factors; slab.

1. Introduction

Since structures with all of its components must always be designed to carry some reserved load above what is expected under normal use, the magnitude of live loads under service load conditions has been prescribed in most design codes by specific values according to their uses. It has also been mentioned that all structural components should be additionally designed to carry either distributed or concentrated loads, whichever produces greater stress (BSI 1990, UBC 1991). The structural members of buildings, however, have been frequently designed based on specified distributed loads without additional consideration for the concentrated loads. Consequently, many structural problems have occurred with the structural members exposed to concentrated loads. In bridges, continuously affected by moving wheel loads, the live-load effects have been increased by an allowance for the impact factor defined as the ratio of maximum dynamic response to maximum static response. Moreover, some strict regulations for both concrete cover and the amount of distributed reinforcing bars have been adopted to minimize the concentrated load effects to a structure.

The loading conditions in parking garages is not greatly different from that of bridges, excepting

† Assistant Professor
‡ Graduate Student

with a difference in the limited vehicle weight (AASHTO 1992, KSCE 1995, UBC 1991). Nevertheless, it has been almost impossible to take into consideration the wheel load effects in design, since the specifications for a standard design vehicle of 2.4 tons is still not clearly described in any design code related to parking garages (BSI 1990, DIN 1972, UBC 1991); accordingly, the application of concentrated wheel loads, while maintaining wheel distance, has been frequently ignored in spite of its importance.

To solve that problem in practice and to consider concentrated wheel loads effectively, a simplified new design method for parking garage slabs is proposed in this paper. After determining a standard design vehicle through the investigation of small to medium vehicles made in Korea, finite element analyses were conducted to obtain the maximum member forces at each slab location. The equivalent vehicle load factors, represented as the ratio of the structural member forces under a standard vehicle of 2.4 tons to those under distributed loads of w=500 kg/m^2 specified in most design codes, (BSI 1990, DIN 1972, UBC 1991) are introduced. Then using the proposed load factors, the required member forces of moving vehicle loads can be easily determined without taking additional sophisticated numerical analyses for the concentrated loads. Correlation studies between various design methods were also conducted with the objective to establish the validity of the proposed method. Various structural behaviors under vehicle loads are discussed.

2. Determination of standard design vehicle

Generally, the dimensions of stalls and aisles of parking garages are determined on the basis of details of the vehicles in use. The plan layout can vary with the required static capacity, site dimensions, traffic demands, and access to the entrance, etc. While overall vehicle dimensions have been recommended, even if those can vary from one authority to another, the criterion for the application of vehicle load has not been clearly explained in most design codes. Only concentrated loads are required to be in consideration whenever it is necessary. Exceptionally in UBC, provision for the consideration of concentrated loads consisting of not less than 2,000 lbs (918 kg: about 40% of gross weight of the maximum size vehicle to be accommodated) spaced 5ft (1.5m) nominally on center, without uniform live loads, is made in the area where vehicles are used or stored. The concentrated load effects, in spite of its importance, have not been considered effectively in design practice since details for a standard design vehicle with the gross weight of 2.4 tons is still not described definitely.

In this study, we introduce a standard design vehicle (see Fig. 1) through the investigation of small to medium vehicles, when applying vehicle loads to parking structures and then reviewing the concentrated loads give greater stress. Table 1 represents details of typical vehicles made in Korea, whose gross weight is not greater than 2.4 tons. As shown in this table, wheel base (L2) and wheel spacing (W1, W2) which have important roles in calculating member forces under vehicle loads, represent almost the same values regardless of vehicle types. It is also assumed that two-thirds of the total weight is transferred to the structure through the rear wheels, with a tire contact area of 0.2m by 0.2m. The ratio was determined by referring to DIN 1072, which specifies the smallest design vehicle with a total weight of 3 tons among the local bridge design codes. Even though the direct adoption of the same ratio between front wheels and rear wheels to a standard design vehicle of 2.4 tons seems to be a little conservative, it can be used as a reference value in situations not having any related regulation for a more exact ratio. Based on the schematic drawing of standard

Table 1 Details of investigated vehicles (unit: mm, kg)

Symbols	Dimensions	Values				
		Grandeur	Sonata	Concord	Musso	Bong-Go
TL	Overall length	4,865	4,578	4,550	4,640	4,600
TW	Overall width	1,725	1,756	1,705	1,850	1,690
L1	Front overhang	1,015	858	975	1,010	780
L3	Rear overhang	1,115	1,141	1,055	1,110	885
L2	Axle spacing	2,735	2,579	2,520	2,530	2,930
W1	Front wheel Spacing	1,455	1,455	1,440	1,510	1,450
W2	Rear wheel Spacing	1,405	1,425	1,430	1,520	1,305
WG	Gross weight	1,540	1,255	1,180	2,200	1,410

Table 2 Details of standard vehicle

Gross Weight	2.4 ton
Overall width	2.5 m
Overall length	5.0 m
Wheel spacing	1.5 m
Wheel base	2.5 m
Rear wheel load	0.8 ton
Front wheel load	0.4 ton

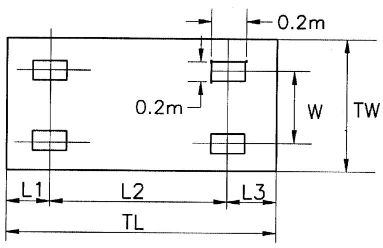


Fig. 1 Schematic drawing of standard vehicle

design vehicle, the wheels are positioned on slabs maintaining 1.0 m distance in width and 2.5 m in length from the wheels of adjoining vehicles. The details of standard design vehicle introduced in this paper are mentioned in Table 2.

3. Impact factor

Concentrated moving loads cause dynamic loads in structures, which are only designed for static loads. These dynamic loads force a structure to behave differently from the structural behavior under static loads. As is well-known from previous studies (Mahil and Martin 1987), the structural behavior under moving loads depends on several variables, i.e., magnitude of loads, surface roughness, moving velocity, and differences in dynamic characteristics between structure and the vehicles. Usually, the dynamic load effects are considered indirectly by introducing the impact factor in most bridge design codes, instead of performing sophisticated dynamic analysis (AASHTO 1992, KSCE 1995). There are currently several definitions for the impact factor as reported in the literature; eight different definitions are also identified by Bakht *et al.* (1989). From among those definitions, an impact factor represented in terms of span length has been broadly adopted (AASHTO 1992).

$$I = 15/(L+40) \leq 0.3 \tag{1}$$

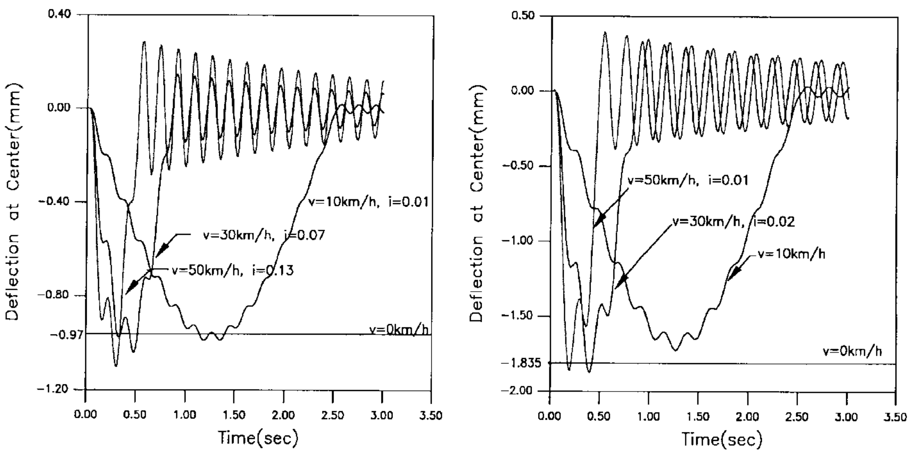
where L is the length in meters of the portion of the span that is loaded to produce the maximum stress in the member.

In recent years, some questions have been raised on whether the current provision on impact factors is adequate when simulating the present traffic situation, since it was made several decades ago when vibration problems were scarcely accounted for. Therefore, extensive empirical and analytical studies have been performed to investigate its exact behavior, and many researchers have suggested impact factors with more realistic and simplified formulas (Akin 1989, Bakht 1989, Yang and Lin 1995). Since the dynamic effects due to the application of moving vehicles must be also considered in parking garages, the impact factor has been already involved in the recommended distributed loads, as set forth in Table 3 (KSCE 1995).

Unlike the distributed loads, however, no related design specification for parking garages has mentioned a formula for the impact factors in the case of vehicle loads of 2.4 tons. This means that many studies need to be conducted in order to establish a rational formula for impact factors, because parking garage structures show two-way behavior, unlike bridges which are assumed to exhibit one-way behavior. Fig. 2 represents the numerical results describing different dynamic responses between the one-way behavior of a beam and the two-way behavior of slab. The results indicate that the moving load effect is very small for both members because of the relatively slow moving of the load. However, there is some discrepancy in deflection time histories at the center of each member. Besides, the impact factor for the slab seems to be smaller than that of the beam, but the deflection pattern indicates that both members behave very similarly. With the objective of evaluating the impact factors for parking garage structures, moving load tests and impact tests were carried out (Yun and Kwak 1996). Nevertheless, the obtained results are not included in this paper, due to the restrictions on collected data. Instead, the impact factor of 0.3 (the maximum value specified in Eq. 1) is used to consider the dynamic effects by vehicle loads, because the span length of the slabs does not exceed 10 m in parking garage structures. When sufficient experimental data are collected and a reasonable impact formula is established, the exact dynamic effects can be considered. For example, the calculated member forces will be revised by multiplying the ratio of impact factor by 0.3. More details can be found elsewhere (Kwak and Song 1997).

Table 3 Design distributed loads (unit: kg/m^2)

Category	Usage	Live loads
Driveway and Parking area	A. light vehicle	300
	B. medium vehicle	500
	C. truck, heavy vehicle	1,200



(a) Simply Supported Beam of 7 m (b) Simply Supported Slab of 7 m by 7 m

Fig. 2 Dynamic response of structural members

4. Effects of concentrated loads

A slab is a structural member carrying an out of plane external load that causes bending moments. The basic concept of its design is to ensure that at service loads, the bending moments and shear forces of the member do not exceed the moment and shear resistant capacities of the section, and that the local deflection is within the allowable range. Once the uniformly distributed loads are determined, the sectional moments of the slab are calculated, based on Eqs. (2) to (5) in Table 4, which are derived from the assumption of clamped edges at all four sides. Especially, it can be found that those formulas came from the elastic beam theory, and positive moments are increased 1.333 times to take the elastic deflection of edge beams into consideration.

When the uniformly distributed load is applied on the slab, the maximum design moments at each location can be then calculated directly by substituting the load into Eqs. (2) to (5) in Table 4. When the concentrated wheel loads are applied, in contrast to an example for the uniformly distributed load, the maximum design moments at each location do not occur at the same time. Hence, using the influence surfaces derived from the Navier solution for plate bending, the locations to apply the wheel loads while maintaining the wheel distances are determined at each direction

Table 4 Maximum design moments at each location on strips of unit width [9]

Direction	Location	
	Middle Strip	Edge Strip
Short Span	$\frac{1}{18}w_x l_x^2$ (2)	$\frac{1}{12}w_x l_x^2$ (3)
Long Span	$\frac{1}{36}w_x l_x^2$ (4)	$\frac{1}{24}w l_x^2$ (5)

Note : l_x = the length of the short span; l_y = the length of the longer span; $w_x = \frac{l_y^4}{l_x^4 + l_y^4} w$

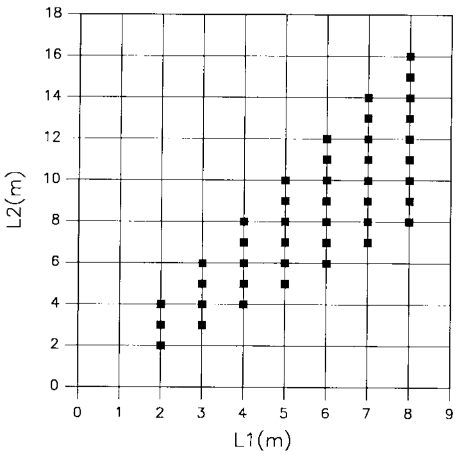


Fig. 3 Construction of section dimensions for slabs

(see Fig. 6). The left side of Fig. 6 represents the influence surfaces for the center of each location of a plate with restrained edges. As shown in these influence surfaces, the portions occupying the ordinates of greater than or equal to 1 on the whole area of the slab are relatively small, and the ordinates rapidly decrease far away from the maximum ordinate point. Consequently, in spite of its relatively small gross weight, a concentrated wheel load placed at the maximum ordinate point may exhibit larger member forces than the uniformly distributed load applied over the entire slab. That is, the concentrated load effect increases as the slab size decreases.

To evaluate the wheel load effects, the overall dimensions of slabs with the short-span length (L1) of 2 m to 8 m and the corresponding aspect ratios (L2/L1) from 1 to 2 are decided to be coincident with the frequently used dimensions in design. A systematic construction of section dimensions for slabs is suggested in this study as shown in Fig. 3, which also represents all the possible slab sections that can be generated.

In analytical investigations for the effects of wheel loads on slabs, as mentioned in previous studies (Westergaard 1943, Woodring 1968), one of the problems is that the ordinary theory of flexure of plates indicates that moments under a load approach infinity as the area over which the load acts approaches zero. In overcoming this difficulty, Westergaard (1943) used a “special theory” to compute the moments in the vicinity of the load, and then concluded that the use of a loaded area

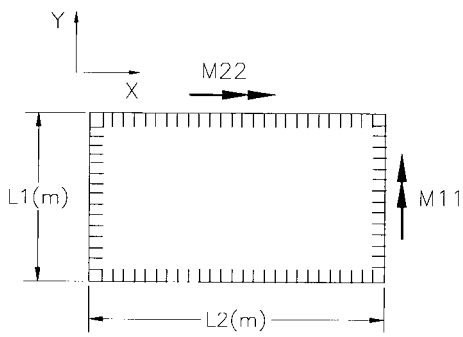


Fig. 4 Adopted sign conventions

was necessary whenever the load was distributed over a circle area whose diameter, a, was less than 3.45 t, where t means slab thickness. In addition, Westergaard's paper includes consideration of the effects of multiple loads along with the derivation of an equivalent width of slab, which may be treated as a beam in designing a bridge slab, a concept that is widely used by bridge designers.

Differently from the bridge slabs, however, a parking garage slab represents two-way behavior. Woodring and Siess (1968) used a combination of fine mesh finite difference solutions plus the moment distribution scheme in order to develop an influence surface for moments in the slabs. One of the conclusions from that study was that a loaded area which is more realistically representative in a vehicular tire print, can produce governing mid-span positive moments in many slab structures. They also found that this positive moment under a mid-span concentrated load was not very sensitive to the support conditions at the edge of the slab, and the moment per unit width converged to m = 0.28 P when a slab was clamped on all sides and subjected to a mid-span load P.

A reinforced concrete slab was modeled using plate elements which can also sustain both shear forces and bending moments, and Fig. 4 shows the sign conventions adopted in this study. In conducting the numerical analysis, the finite element used in this study was a quadratic plate element developed by Choi and Kim (1988). This element is established by the combined use of reduced integration and then the addition of nonconforming displacement modes, and gives very good results in a linear elastic analysis. To investigate the singularity problem according to the application of point loads, the convergence test was also performed for the finite element used with a square plate clamped at all four sides.

As shown in Fig. 5, the positive and negative moments per unit width converged to $m^+ = 0.28$P and $m^- = -0.26$P, respectively as small as the used finite element mesh size in the case of considering the wheel print of 0.2 m $\times$ 0.2 m. However, the positive moments per unit width under a mid-span point load diverged. Based on the obtained results, a wheel print which is located at either the maximum positive or negative ordinate point is considered, but the other wheel prints are not considered since the unit moment intensities reduce very quickly as one moves away from the maximum load point. In obtaining the maximum design moments per unit width under vehicle loads, the element mesh size, b, less than 0.05 L was selected.

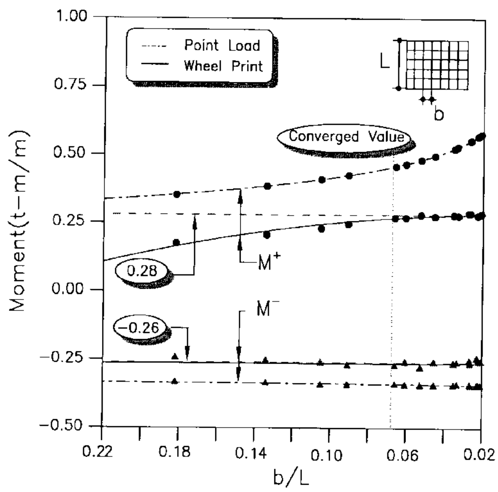
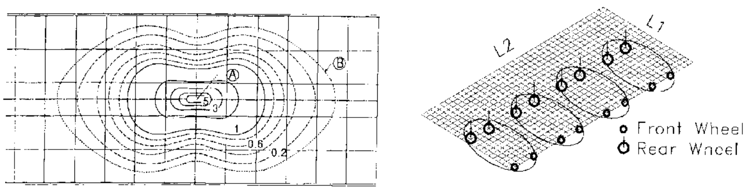


Fig. 5 Convergence test for the finite element used

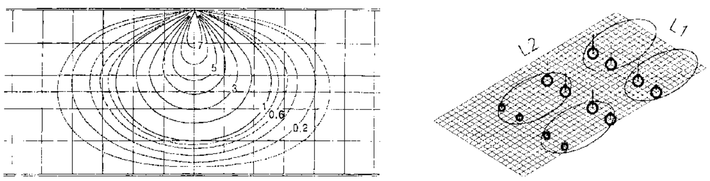
5. Application of concentrated loads

Based on the influence surfaces, the positions of wheel loads which produce maximum member forces at each location can be determined, as shown at the right side of Fig. 6. From Fig. 6(a), which shows the maximum center-moment influence surface in a short span direction, it can be inferred that a wheel load applied at the center (point Ⓐ in Fig. 6a) affects the member force about fifty times as large as one at point Ⓑ. Because of the difference in ordinates, the calculation of maximum member forces requires the following procedures: (1) apply a rear wheel print to the maximum ordinate point to establish a datum point; (2) locate all other possible wheel loads while maintaining the distances according to details of standard design vehicle (see Table 2 and Fig. 1); and (3) conduct finite element analysis with those designated wheel loads.

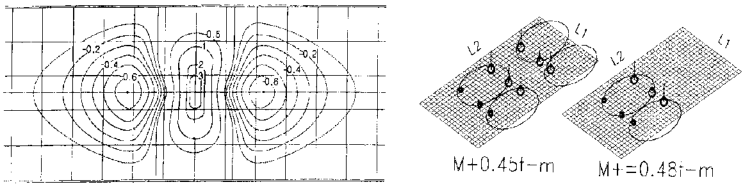
In the case of the maximum support moment in the long span direction, as shown in Fig. 6(d), the loads located on the right half of the slab can not affect the member force, so those forces can be disregarded for convenience in calculation. Also, the maximum center-moment influence surface in the long span direction (Fig. 6c) shows the existence of a region which represents the adverse effect (i.e., a decrease of member force attended by an increase of applied loads) as the aspect ratio of the



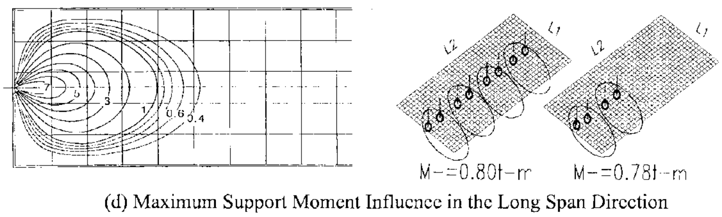
(a) Maximum Center Moment Influence in the Short Span Direction



(b) Maximum Support Moment Influence in the Short Span Direction

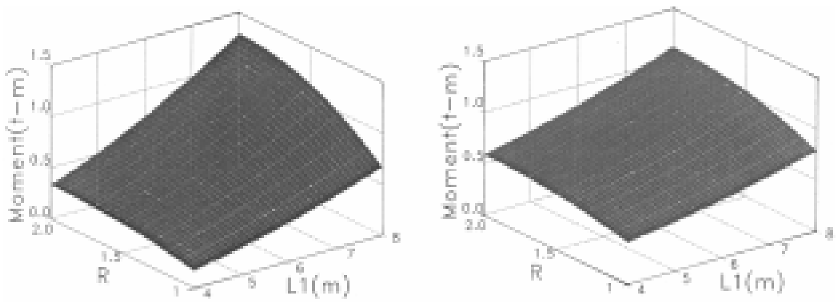


(c) Maximum Center Moment Influence in the Long Span Direction



(d) Maximum Support Moment Influence in the Long Span Direction

Fig. 6 Influence surfaces and application of vehicle loads



(a) Uniform Load of $w = 500\ kg/m^2$ (b) Vehicle Load of $P = 2.4(1+0.3)$ *tons*

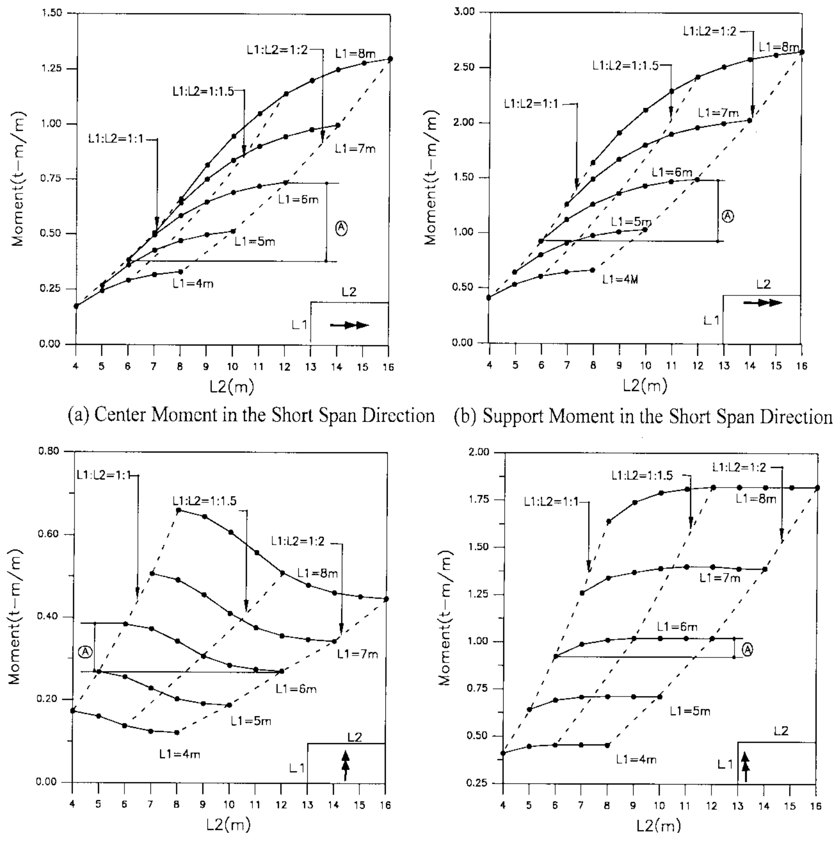
Fig. 7 Maximum center moments in the short span direction

slab is increased. Accordingly, the application of only two vehicles gives larger member forces than a case where four vehicles are applied overlooking the adverse effect. From the characteristics of influence surfaces mentioned above, the following can be inferred: (1) The member forces are predominantly influenced by many factors. Namely, these are total weight of vehicle, the weight ratio of wheels, axle spacing, and wheel spacing; (2) The concentrated wheel loads may cause greater member forces than uniformly distributed loads in spite of relatively small gross weight; and (3) The wheel load effects are more remarkable for the positive moments than for the negative moments because the region with relatively high ordinates is concentrated in a confined area around the center point.

6. Estimation of member forces

The maximum design moments at each location of each slab are calculated both by the application of the uniformly distributed load of w=500 kg/m^2 and vehicle load of P=2.4(1+0.3) tons, following the previously mentioned description. As shown in Fig. 7 which represents the profiles of positive moments in the short span direction, the member forces under uniformly distributed loads vary a little more than those under vehicle loads, as the short span length L1 and aspect ratio of slab dimensions R (i.e., the long span length L2 over short span length L1) are increased. Also, there is no remarkable variation in member forces followed by an increase of slab size in the case of vehicle loads.

More details can be found in Figs. 8 and 9 which represent the variations of member forces in a two-dimensional plane. The comparison of member forces under the design uniform load of w=500 kg/m^2 (see Fig. 8) with those under the standard vehicle load of P=2.4(1+0.3) tons (see Fig. 9) leads to the following results. First, as the shorter span length L1 is increased and the span ratio R(L1:L2) varies from 1 to 2, both positive and negative moments in the short span direction gradually increase. But, on the other hand, the moments in the long span direction decrease and then converge to certain limit values. Such a tendency represents the movement of the load in the short span direction in accordance with an increase of span ratio, and agrees well with the general behavior of two-way slabs. Second, the increase of member forces is more remarkable in the case of uniformly distributed loads (Ⓐin Fig. 8), as compared with the case of vehicle loads (Ⓑ in Fig. 9). Finally, the member forces of the vehicle loads increase up to about three times more than those of the uniformly distributed loads when the slab dimensions are relatively small, but those differences are



(a) Center Moment in the Short Span Direction (b) Support Moment in the Short Span Direction

(c) Center Moment in the Long Span Direction (d) Support Moment in the Long Span Direction

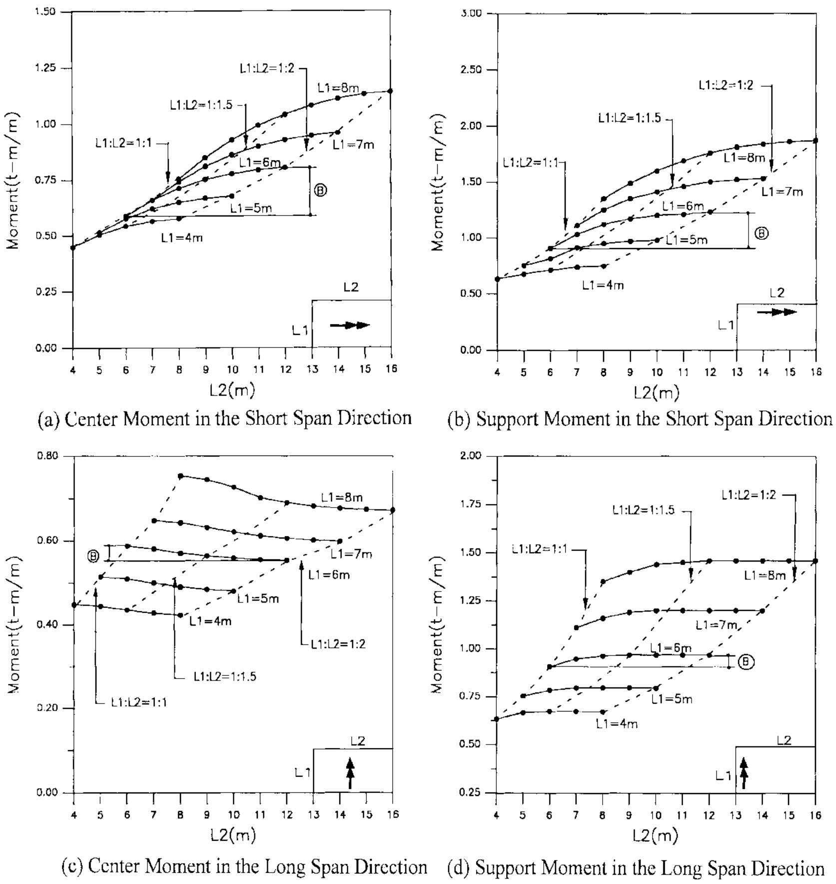
Fig. 8 Member forces under uniformly distributed load of w=50 kg/m^2

reversed as the slab dimensions increase.

Fig.10 represents variations of member forces for the slabs with shorter span lengths of either 4 m, 6 m, or 8 m. As shown in this figure, the center moments in the long span direction (see Fig. 10c) are always governed by the vehicle loads through the entire span length. This result originates from the characteristics of the slab influence surface. That is, the region which has the favorable effect is distributed narrowly at the center. But on the other hand, the region which gives an adverse effect is distributed broadly at the middle of each side (see Fig. 6c). In the other directions, the more the span length decreases, the more the wheel load effect increases. Therefore, the calculation of live load moments based on an uniformly distributed load may lead to an underestimation of the resisting capacity of the slab especially when the short span length is less than 8 m. Moreover, there is some possibility for inherent structural defects in parking garages, if those structures are still designed without consideration of these concentrated wheel loads.

7. Determination of equivalent vehicle load factors

Since the actual live loads are not uniformly distributed loads but concentrated vehicle loads, and



(a) Center Moment in the Short Span Direction (b) Support Moment in the Short Span Direction

(c) Center Moment in the Long Span Direction (d) Support Moment in the Long Span Direction

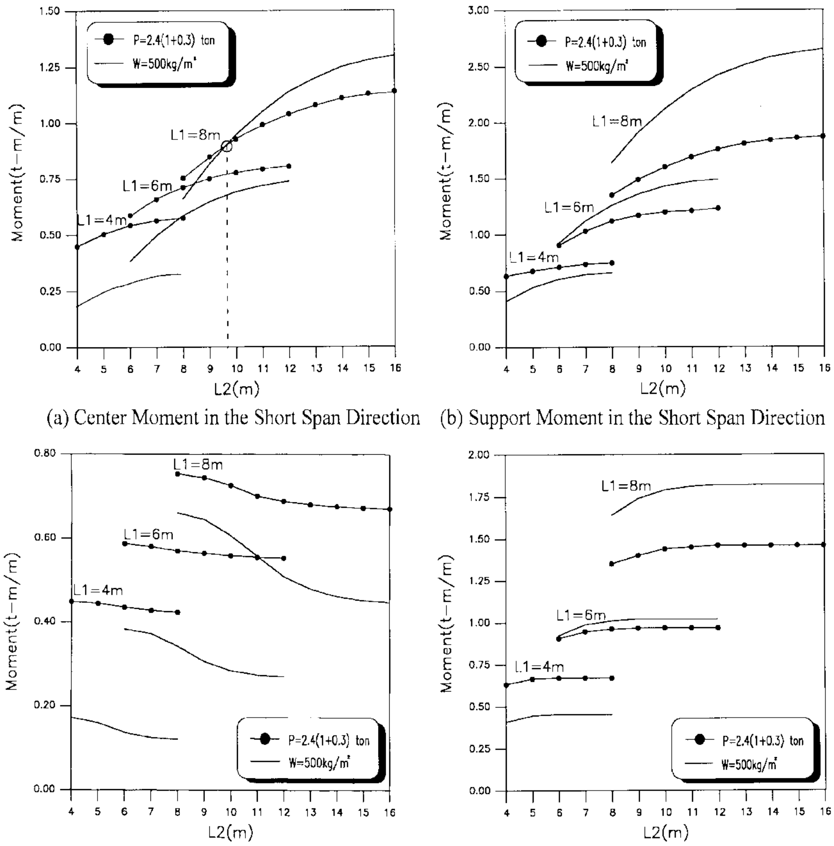
Fig. 9 Member forces under vehicle load of P=2.4(1+0.3)/tons

the structural behavior is also governed by the concentrated vehicle loads in a parking garage, it is absolutely required to conduct structural analyses for the concentrated wheel loads. However, the consideration of vehicle loads costs the structural engineers much time and effort, from the modeling of structures to sophisticated numerical analyses. To remove those complex procedures effectively in practice, equivalent vehicle load factors are introduced in this study.

Multiplying the member forces obtained by the application of uniformly distributed load by the equivalent vehicle load factors, the required design member forces under vehicle loads can be obtained easily. Equivalent vehicle load factor, as shown in Eq. (6), has been defined as the ratio of member forces, with a vehicle loads of P=2.4(1+0.3) tons to the member forces under uniformly distributed load of w = 500 kg/m^2. If any calculated factor has a value greater than 1, it means that the obtained member force for the uniformly distributed load also needs to be increased to resist the vehicle loads with the limiting vehicle weight of 2.4 tons, as defined in most design codes.

$$F=\frac{M_p}{M_w} \tag{6}$$

where F is the equivalent vehicle load factor, M_p and M_w are the live load moments calculated by the design vehicle loads of P=2.4(1+0.3) tons, and the design uniform load of w=500 kg/m^2,



(a) Center Moment in the Short Span Direction (b) Support Moment in the Short Span Direction

(c) Center Moment in the Long Span Direction (d) Support Moment in the Long Span Direction

Fig. 10 Comparison of member forces

respectively.

The calculated equivalent vehicle load factors for all slabs are represented with dots in Fig. 11. From this figure, it can be found that the equivalent vehicle load factors, *F*, except for the case of positive moments in the long span direction, decrease as the short span length of slabs increase. In addition, the equivalent vehicle load factors are converged on certain limit values as the aspect ratio of the slabs increases. Moreover, if the short span length of the slab is larger than 6 m, the equivalent vehicle load factors for negative moments in both directions become smaller than 1. It means that there is no necessity to consider the vehicle load effect since the uniformly distributed loads govern structural behavior. To determine a reasonable regression formula, an overall review of the effect of each design variable was conducted. Consequently, it was found that the variation of a short span length L1, and aspect ratio *R*, have the greatest effects on the equivalent vehicle load factors among all of the design variables for the slabs. Therefore, a form of regression formula as represented in Eq. (7) was choosen, and the obtained regression results are mentioned in Eqs. (8) to (15) in Table 5. Especially, the correlation coefficients r^2 in Table 5, representing the values close to 1.0, imply that the proposed equations can simulate the equivalent vehicle load factors effectively.

$$F = (aL^b + c) \times (AR^2 + BR + C) \tag{7}$$

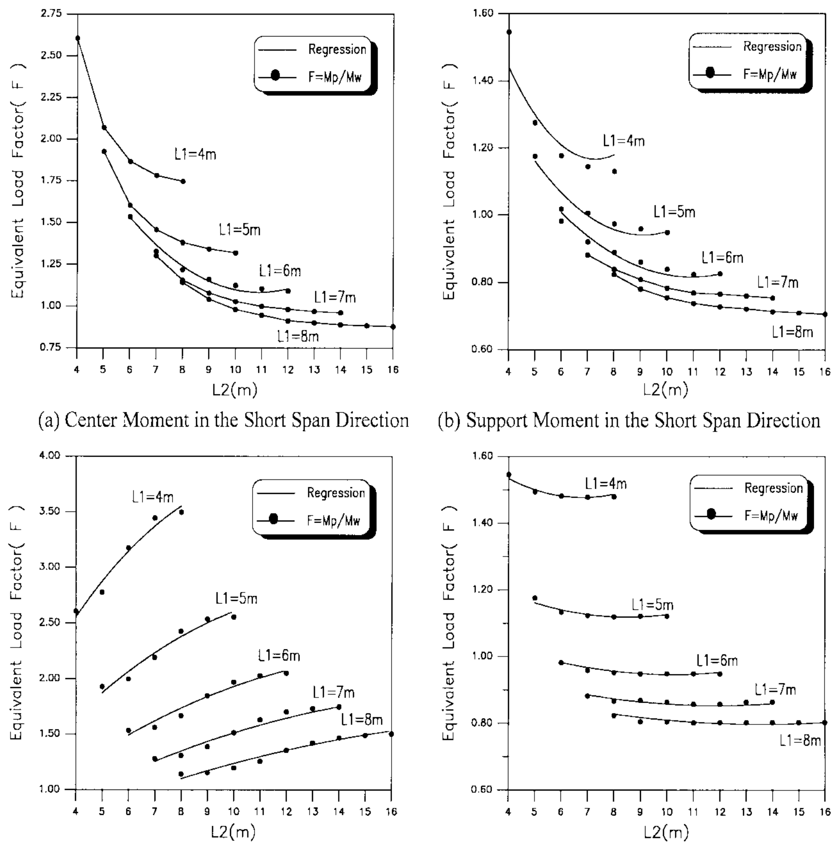
Table 5 Proposed equivalent vehicle load factors(F)

Location	$F = F_1 \times F_2 = (aL^b + c) \times (AR^2 + BR + C)$		
	$F_1(L) = aL^b + c$	$F_2(R) = AR^2 + BR + C$	r 2
A	$3.66L^{-2.01} + 0.10$ (8)	$3.41R^2 - 12.38R + 16.72$ (9)	0.990
B	$3.22L^{-1.94} + 0.18$ (10)	$1.03R^2 - 3.73R + 6.34$ (11)	0.978
C	$1.83L^{-1.86} + 0.04$ (12)	$-2.03R^2 + 11.89R + 4.60$ (13)	0.995
D	$4.44L^{-2.61} + 0.10$ (14)	$0.53R^2 - 1.80 + 8.33$ (15)	0.999

Note: **A** = Center in the short span direction; **B** = Support in the short span direction; **C** = Center in the long span direction; **D** = Support in the long span direction; L = Length of the shorter span L1; R = Aspect ratio of slab L2/L1.

where L is the short span length L1, R is the aspect ratio of slab (L2/L1); and a, b, c, A, B, and C are coefficients which will be determined by regression.

Using the obtained formulas of Eqs. (8) to (15) in Table 5, the design member forces according to the vehicle loads can be calculated directly by Eq. (16). That is, no other additional analysis is necessary, because the member forces at each location due to the vehicle loads were already



(a) Center Moment in the Short Span Direction (b) Support Moment in the Short Span Direction

(c) Center Moment in the Long Span Direction (d) Support Moment in the Long Span Direction

Fig. 11 Equivalent vehicle load factors

Table 6 Equivalent vehicle load factors(F) at each location

Sectional Dimension (L1×L2)	**A**	**B**	**C**	**D**
4m×4m	2.5514	1.5330	2.5514	1.5530
4m×8m	1.8082	1.1797	3.5499	1.4872
8m×8m	1.0986	0.8274	1.0986	0.8274
8m×16m	0.8574	0.6981	1.5285	0.8026

Note: **A**, **B, C**, and **D**: the same descriptions with those used in Table 5.

obtained by applying all of the possible wheels while at the same time maintaining wheel spacing and base.

$$M_i(\text{design}) = F_i \times M_i\ (500) \tag{16}$$

Where M_i(design) and M_i(500) imply the live load moments by both the vehicle loads of P=2.4(1+0.3) tons, and by the uniformly distributed load of w=500 kg/m^2 at i-location, respectively; and F_i is the equivalent vehicle load factor at i-location which was calculated from Eqs. (8) to (15).

8. Numerical applications

Since it was impossible to find from previous studies the experimental data simulating the loading conditions for parking garages, comparisons with numerical calculations were therefore conducted. To verify the effectiveness of the design procedure introduced in the study, typical slab sections of 4 m × 4 m, 4 m × 8 m, 8 m × 8 m, and 8 m × 16 m were selected. The calculated equivalent vehicle load factors at each location according to Eqs. (8) to (15) in Table 5 are shown in Table 6. For the convenience of calculation, the factors for the square slabs are calculated on the basis of the equation for the long span direction, since a negligible difference may exist between the two directions.

All the factors for slabs of 8 m × 16 m, except one for the positive moment in the long span direction marked with ***C*** in Table 6, have values smaller than 1. This means the effects of vehicle loads are so small that the uniformly distributed load governs the structural behavior as the slab dimension is increased. But the center moment in the long span direction is always governed by the vehicle loads. The member forces of slabs, due to the direct application of vehicle loads, are compared with those obtained from the multiplication of the results due to the uniformly distributed load by the calculated equivalent vehicle load factors F. Table 7 shows that the equivalent vehicle load factors suggested in this study effectively describe the vehicle load effects without taking sophisticated analysis procedures. However, as shown in the first and second rows in Table 7 (Design Code and W cases), there are some differences in member forces in spite of the same distributed load of w=500 kg/m^2. Those differences came from the inclusion of pattern loading effects in design codes as mentioned previously.

The pattern loading effect has been considered separately from the application of distributed load in practice to remove the under-estimation of member forces occurring as a result of pattern loads. Actually, the parking garage is a typical structure affected by strip loading, due to its sequential plan layout of stalls and aisles, so that this effect must be considered. Moreover, the reduction of loads in view of the possibility of coincident maximum loading may not be applicable to the parking garage.

Based on that, the inclusion of pattern loading effects may be achieved indirectly just by multiplying the member forces according to the application of the current design code in Table 7 instead of the direct application of the distributed load (*W* in Table 7) by the obtained vehicle load factors. More details, including the equivalent vehicle load factors for beams and girders, and regression in the case of direct consideration for the pattern loading, can be found elsewhere (Kwak and Song 1997).

Also, the obtained results of $W \times F$ in Table 7 are further compared with reference values which are caluculated on the basis of classical plate bending theory (Timoshenko 1959). According to the Navier solution, the deflection surface for a simply supported rectangular plate under a single load *P* concentrated at any given point $x=\xi$, $y=\zeta$, can be expressed as follows:

$$w=\frac{4P}{\pi^4 abD}\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\frac{\sin(m\pi\xi)\sin(n\pi\zeta)}{\left(\frac{m^2}{a^2}+\frac{n^2}{b^2}\right)^2}\sin\left(\frac{m\pi x}{a}\right)\sin\left(\frac{m\pi y}{b}\right) \tag{17}$$

where *D* means the flexural rigidity of a plate, *a* and *b* are the span length along the *x*-axis and *y*-axis, respectively.

Table 7 Comparison of member forces according to the design methods

Dimensions	Methods	**A**	**B**	**C**	**D**
4m × 4m	Design Code	0.222	0.333	0.222	0.333
	W	0.172	0.409	0.172	0.409
	P	0.448	0.632	0.448	0.632
	$W \times F$	0.440	0.630	0.440	0.630
	Reference Value	0.441	0.596	0.441	0.596
4m × 8m	Design Code	0.418	0.628	0.222	0.333
	W	0.329	0.661	0.121	0.453
	P	0.574	0.747	0.423	0.670
	$W \times F$	0.590	0.780	0.429	0.673
	Reference Value	0.589	0.638	0.420	0.759
8m × 8m	Design Code	0.889	1.333	0.889	1.333
	W	0.660	1.640	0.660	1.640
	P	0.753	1.350	0.753	1.350
	$W \times F$	0.730	1.350	0.730	1.350
	Reference Value	0.657	1.200	0.657	1.200
8m × 16m	Design Code	1.673	2.510	0.889	1.333
	W	1.300	2.650	0.447	1.820
	P	1.140	1.870	0.671	1.460
	$W \times F$	1.110	1.850	0.683	1.500
	Reference Value	1.207	1.640	0.686	1.355

Note: **A**, **B**, **C** and **D**: the same descriptions with those used in Table 5; Design Code = Member forces calculated by the current design code with the distributed load of w=500 kg/m^2 (see Table 4); *W* = Member forces by finite element analysis with the distributed load of w=500 kg/m^2; *P* = Member forces by finite element analysis with the vehicle loads of P=2.4(1+0.3) tons; $W \times F$ = Member forces obtained by multiplying the second row of *W* by the equivalent vehicle load factors; Reference Value = Member forces obtained by the classical bending theory.

$$w_1 = -\frac{a^2}{2\pi^2 D} \sum_{m=1,3,5\ldots}^{\infty} E_m \frac{(-1)^{(m-1)/2}}{m^2 \cosh(\alpha_m)} \cos\left(\frac{m\pi x}{a}\right) \cdot \left(\frac{m\pi y}{a} \sinh\left(\frac{m\pi y}{a}\right) - \alpha_m \tanh\alpha_m \cosh\left(\frac{m\pi y}{a}\right)\right) \tag{18}$$

$$w_2 = -\frac{b^2}{2\pi^2 D} \sum_{m=1,3,5\ldots}^{\infty} E_m \frac{(-1)^{(m-1)/2}}{m^2 \cosh(\beta_m)} \cos\left(\frac{m\pi y}{b}\right) \cdot \left(\frac{m\pi x}{b} \sinh\left(\frac{m\pi x}{b}\right) - \beta_m \tanh\beta_m \cosh\left(\frac{m\pi x}{b}\right)\right) \tag{19}$$

By using the Eqs. (18) and (19) which represent the deflection surface of the plate simply supported and bent by moments distributed along the edges at $y = \pm b/2$ and $x = \pm a/2$, the boundary conditions for a slab clamped on all sides can be expressed as the following relations:

$$\left(\frac{\partial w}{\partial y}\right)_{y=b/2} + \left(\frac{\partial w_1}{\partial y} + \frac{\partial w_2}{\partial y}\right)_{y=b/2} = 0, \left(\frac{\partial w}{\partial x}\right)_{y=a/2} + \left(\frac{\partial w_1}{\partial x} + \frac{\partial w_2}{\partial x}\right)_{x=a/2} = 0 \tag{20}$$

After determining the constant E_1, …, E_m, F_1, …, F_m, the bending moments, finally, can be calculated on the basis of the plate bending theory and the obtained values are mentioned as Reference Values in Table 7.

As shown in Table 12, the proposed method in this study effectively describes the point load effects in comparison with those in the case of P and Reference Values. Also, the numerical analysis for the concentrated moving loads by adopting finite element analysis or the classical approach requires more tedious and complex procedures than the proposed method.

9. Conclusions

A simple, but effective, design method for slabs in parking garage structures is presented in this study. Unlike the classical approaches adopted in consideration of concentrated wheel loads, the determination of design moments at each location can be now achieved easily by using the proposed equivalent vehicle load factors, since those factors include all of the important factors when analyzing the concentrated loads.

As shown in numerical applications, the wheel loads govern the structural behavior in spite of its relatively small total weight. Especially, the wheel load effects are dominant for the center moment in the long span direction. It is also found that the vehicle load effects must be considered in the design of parking garages, as it is in the design of bridges in order to remove its inherent structural defects, even if the vehicle weight is relatively small. However to reach a more rational approach, extensive studies on the impact factors of slabs which consider two-dimensional behavior need to be conducted.

Acknowledgements

The research presented in this paper was sponsored partly by the Samsung Corporation, Construction and Engineering Group. Their support is greatly appreciated.

References

AASHTO (1992), *Standard Specifications for Highway Bridges*, AASHTO Inc.
Adolf Pucher (1977), *Influence Surface of Elastic Plates*, Springer-Verlag Wien.
Akin, John E. and Mofid, Massood (1989), "Numerical solution for response of beams with moving mass", *J. of Struct. Engnr, ASCE*, **115**, 120-131.
Bakht, B. and Pinjarkar, S.G. (1989), "Review of dynamic testing of highway bridges", TRB 880532, SRR-89-01, 1-33.
British Standard Code of Practice CP3 (1990), *Chapter V. Loading: Part 1*, British Standard Institution.
Choi, C.K. and Kim, S.H. (1988), "Reduced integration, nonconforming modes and their coupling in thin plate elements", *Computers & Structures*, **29**, 52-62.
DIN 1072 (1983), *Standard Design Loads for Buildings: Live Loads*, DIN Deutsches Institut fur Normung.
DIN 1055 (1983), *Design Loads for Building: Live Loads*, DIN Deutsches Institute fur Normung.
IMSL Library (1982), User's Manual, Fortran Subroutines for Mathematics and Statics, 1-4, IMSL Inc.
KSCE (1995), *Building Code Requirements for Reinforced Concrete*, Korea Society of Civil Engineers, Seoul.
KSCE (1995), *Standard Specifications for Highway Bridges*, Korea Society of Civil Engineers, Seoul.
Kim, K.H. (1994), *Design of Parking Garage Structures*, Architectural Culture, Seoul.
Kwak, H.G., Song, J.Y. (1997), "Equivalent vehicle load factors for girder and beam of parking garage structures", *J. of Comp. Struct. Engnr Inst. of Korea*, **10**, 15-28.
Kwak, H.G., Song, J.Y. (1997), "Equivalent vehicle load factors for slab of parking garage structures", *J. of Struct. Engnr KSCE*, **17**, 529-540.
Mahil J., Inbanathan and Martin Wieland (1987), "Bridge vibrations due to vehicle moving over rough surface", *J. of Struct Engnr, ASCE*, **113**, 1994-2008.
Stanton, John F. (1982), "Point loads on precast concrete floors", *J. of Struct. Engnr, ASCE*, **109**, 2619-2637.
Timoshenko, S.P. and Woinowsky-Krieger, S. (1959), *Theory of Plates and Shells*, McGraw-Hill, New York.
UBC (1991), *Uniform Building Code*, International Conference of Building Officials.
Westergaard, H.M. (1943), "Stress concentrations in plates loaded over small areas", *J. of Struct. Div., ASCE*, **108**, 831-856.
Woodring R.E. and Siess, C.D. (1968), "Influence surfaces for continuous plates", *J. of Struct. Div., ASCE*, **94**, (ST1), 211-226.
Yang, Y.B. and Lin, B.H. (1995), "Impact formulas for vehicles moving over simple and continuous beams", *J. of Struct Engnr ASCE*, **121**, 1644-1650.
Yun, C.B., Kwak, H.G. (1996), "The evaluation of structural behavior in precast concrete underground parking garage using the site instrumentations", Report No. 97-z05-175. Samusung Corporation, Seoul.