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TBSC 2018 Provisions on Design Shear Forces for Buildings with Rigid Basements

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ABSTRACT

In this study, a representative reinforced concrete building structure incorporating laterally-rigid basement levels is first analyzed under design-level earthquake demands, by applying alternative linear elastic analysis methodologies recommended in the 2018 Turkish Building Seismic Code (TBSC 2018) for buildings with rigid basements. Subsequently, a nonlinear model of the structure is generated, and nonlinear response history analyses are conducted for the structure, under selected ground acceleration records that are scaled to represent design-level and maximum-considered ground motion levels. Nonlinear response history analysis results obtained for the seismic shear force demands developing along the stories of the building, as well as on individual structural wall cross-sections, are compared with design-basis linear elastic analysis results. Upon comparative evaluation of the analysis results, the reliability/conservatism of the alternative linear elastic analysis methodologies specified in TBSC 2018 for obtaining design-basis seismic shear force demands on buildings with rigid basements are discussed. The inconsistencies between the code-specified alternative analysis methods are identified, and potential improvements to code provisions are suggested.

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1. INTRODUCTION

In strength-based design of buildings with laterally-rigid basement levels, due to significant differences in the vibration characteristics, ductility attributes, and nonlinear dynamic response characteristics of the relatively flexible superstructure and the rigid basement substructure enclosed by perimeter walls, determination of the design-basis seismic demands developing on the entire structural system is not straightforward. The general procedure for estimation of design-basis seismic demands in strength-based design includes utilization of linear elastic analysis methods together with application of seismic load reduction factors on the analysis results. Seismic load reduction factors are defined to very crudely represent the seismic demands that depend on the expected (targeted) nonlinear behavior of the structure during a design-level earthquake, depending on the ductility and overstrength characteristics of the structural members/system. In the 2018 Turkish Building Seismic Code (TBSC 2018) [1], the seismic load reduction factor (R_a) corresponding to a particular period of vibration of the structure is correlated with the structural system behavior factor (R) and the system overstrength factor (D). These factors are provided in Table 4.1 of the seismic code for various structural systems. However, since the vibration characteristics and the ductility properties of the rigid basement substructure can be significantly different from the superstructure, application of these factors in strength-based design of structural members located within the laterally-rigid basement levels of a building is not directly possible, and modification of these factors for determining the design-basis seismic demands along the basement levels is required.

Therefore, TBSC 2018 provides several approximate analysis options based on two main modeling/analysis approaches. In the first approach, an analysis model is generated including the masses of both the superstructure and the basement substructure, and the seismic load reduction factor to be used in design of the basement structure is calculated depending on the linear elastic story shear force distribution obtained along the entire structure. In the second approach, the mass of superstructure and the basement floors are considered in two separate analysis models, and analysis results from the two separate stages are combined to obtain the design-basis internal force demands along the basement floors. These two main modeling/analysis approaches are referred to in this paper as the “total structure approach” (TSA) and the “two-stage loading approach” (TSLA). In both approaches, application of the well-known equivalent lateral force analysis (ELFA) and response spectrum analysis (RSA) methods are both allowed in TBSC 2018 for design of the basement structure.

Unfortunately, available research focusing on analysis methods of structures with rigid basements is extremely limited in the literature. In order to assess reliability of fixed base modeling assumption above basement levels, Kocak et al. [2], examined effects of basement rigidity on response of a 2D frame structure gradually increasing the rigidity of the ground floor, and comparing base shear and top displacement results for the superstructure. The importance of differences in analysis results between semi-rigid and rigid basement levels were underlined in the study. Another study that focuses analysis methods of structures with rigid basement levels is Allen et al. [3]. In the study, application of two-stage loading approach during design of two new hospitals and evaluation of an existing hospital was explained. The challenges involved in analyses as well as recommendations for code interpretations of the method were emphasized. Difficulties in load transfer from analysis of the superstructure to the basement model were underlined, and an approximate load combination method for the specific case of multiple towers placed on a single podium was proposed. Ozuygur and Dilsiz [4] evaluated response spectrum analysis results of five different structures with rigid basement levels and different building heights employing two-stage loading approach defined in TBSC 2018. In the study, difficulties in combination of analysis results from separate analysis models (due to different mass definition requirement of the method) at structural member level was underlined, and an approximate yet practical method that does not necessitate any combination was recommended for estimation of seismic demands at basement levels. On the other hand, several examples such as Yuan and Xu [5], Chen and Ni [6], and McBain et al. [7] that focus on two stage analysis methods for multi-story wood or cold-formed steel framed buildings on rigid reinforced concrete basement levels are also available in the literature.

In ASCE 7 [8], a two-stage analysis approach for structures with a flexible upper portion above a rigid lower portion is provided, which can be adopted for buildings with rigid basements. When this analysis approach is compared with the TSLA of TBSC 2018, in both methods, seismic demands on rigid basements are estimated with combination of two separate analysis results. However, differently from TSLA in TBSC 2018, in the ASCE 7 method, two different analysis models are generated for the flexible superstructure and the rigid basement structure. The reduced internal force demands obtained at the fixed supports of the superstructure are transferred to the separate analysis model of the basement structure as externally-applied static loads (axial forces, shear forces, and bending moments) applied on the cross-sections of the vertical structural members at the superstructure/basement interface. In this procedure, the seismically-induced axial forces, shear forces and bending moments transferred from the superstructure to the basement structure are multiplied with (amplified by) the ratio of the seismic load reduction factors defined for the superstructure and the basement structure. However, in ASCE 7, no seismic load reduction coefficient or overstrength coefficient is explicitly defined for the basement of a building. Furthermore, in ASCE 7, seismic demands on the basement (developing due to the mass of the basement floors) are obtained only using the equivalent lateral force procedure, while TBSC 2018 provides procedures for both equivalent lateral force and response spectrum analysis methods.

In Eurocode 8 [9], no explicit provisions are provided for determination of seismic demands on the structural members located within the rigid basement levels of the building, which develop due to the seismic mass of the basement. Only in Section 5.8.1(5), for determination of structural wall design shear forces, the code recommends assuming a plastic hinge development above the topmost basement level and calculating the shear demands on the walls via division of the flexural capacity of the wall to total height of the basement floors. The recommended approach simply assumes the structural walls develop their flexural overstrength (1.2 times its flexural capacity for high ductility class structures) and bending moment diagram along the element is inverse triangle (flexural capacity at the top, zero at the foundation level) along the height of the basements. Additionally, the recommendation also includes extension of the critical region of the walls down to a depth of critical wall height below the topmost basement level. On the other hand, in a technical report prepared for worked examples of Eurocode 8 [10], only the superstructure mass was considered in the analysis model assuming that the masses in basement levels do not influence the analysis results due to extremely small deformations of walls at these levels. Overall, it is important to note that compared to TBSC 2018, in both ASCE 7 and Eurocode 8, the relevant sections on seismic analysis and design of structural members along rigid basement levels of buildings are very brief and mostly vague, and both codes are subject to improvement in terms of providing more detailed and well-defined provisions that can be used for more reliable/systematic and safer (or more economical) design of rigid basement levels of buildings.

Within the scope of this study, both linear elastic and nonlinear models of a representative mid-rise building structure, with a laterally-rigid basement substructure, are generated. Alternative analysis methods specified in TBSC 2018 for strength-based seismic design of structures with rigid basements are applied on the linear elastic analysis model of the structure. The reinforcement in all structural members is designed at the limit, in order to attain the most economical design that conforms with TBSC 2018 provisions, so that significant (code-targeted) nonlinear behavior (flexural, axial/flexural) is expected from the structure under design-level (or larger) seismic demands. Subsequently, to simulate the nonlinear dynamic response of the structure, and to obtain internal shear force demands that inherently represent the validity of the procedures specified in TBSC 2018 for strength-based design of buildings with rigid basement levels, nonlinear response history analyses (NLRHA) are conducted for the structure. Selected ground motions are scaled to the design spectra specified in TBSC 2018 for the so-called DD2 (design-level earthquake with probability of exceedance of 10% in 50 years and a recurrence period of 475 years) and the DD1 (maximum credible earthquake with probability of exceedance of 2% in 50 years and a recurrence period of 2475 years) ground motion levels. In order to evaluate the reliability of the alternative analysis methods recommended in the code for buildings with rigid basements, as well to identify the inconsistencies between the analysis methods and suggest improvements, analysis results obtained using all different linear elastic and nonlinear dynamic analysis procedures are compared. The comparison focuses on the total story shear force demands developing in the building, as well as the shear force demands developing on individual structural wall cross-sections, along the entire height of the building. Even though evaluation of an analysis method requires consideration of wide range of ground motion levels due to the effect of PSHA component on the outcomes, since main objective of this study is evaluation of design-basis demands that are only obtained at a specific ground motion level (design-level), alternative analysis methods are only discussed for the design-level (and just for informative purposes also maximum considered) ground motion level in the following sections.

2. MODELING AND ANALYSIS METHODOLOGY

2.1. Building Properties

The representative reinforced concrete (RC) building with a total height of 32.50 m (Figure 1a) considered in this study comprises nine stories above the ground level in addition to two basement stories, where the heights of the normal and basement stories are typically 2.9 m and 3.2 m, respectively. The superstructure (Figure 1c) is designed as a residential building and the basement levels (Figure 1b) are designed to function as a parking lot. Material grades used in design of the building are C40 class concrete and B420C grade reinforcing steel. The load-bearing system of the superstructure consists of two U-shaped (PC01 and PC02 in Figure 1c) and three planar structural walls (P03-P04 and P05 in Figure 1c), as well as columns and flat plate floor systems incorporating perimeter beams. Thicknesses of the segments of the U-shaped walls are 350 mm for the webs and 350 mm/400 mm (upper seven stories/first four stories) for the flanges. The thickness of three planar walls is 300 mm along the entire height of the building, and the thickness of the walls surrounding the basement floors is 300 mm. The depths of the perimeter beams vary between 300 mm and 500 mm, and the thickness of the flat plate at the superstructure floors is 240 mm, whereas it increases to 300 mm at basement floors.

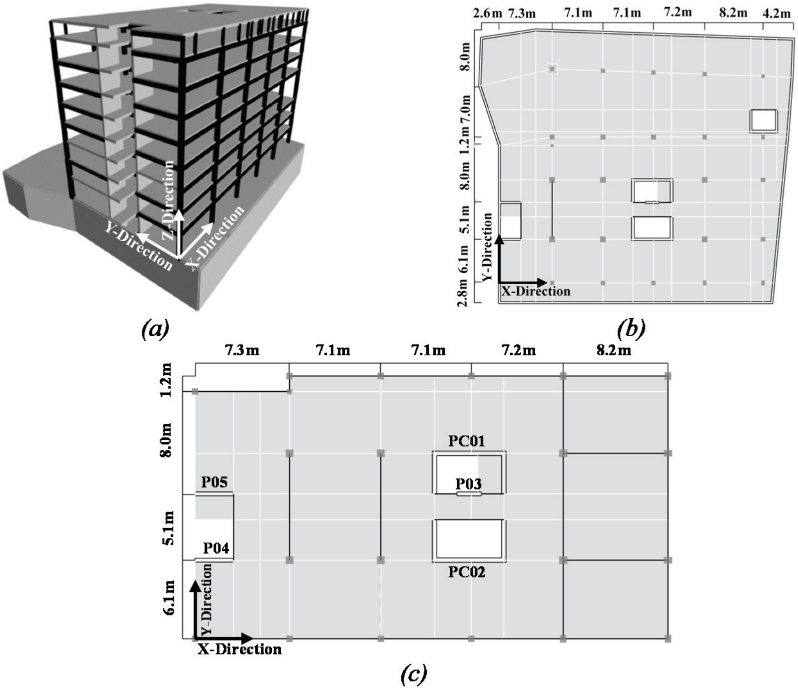


Figure 1 - The archetypal RC building: (a) 3D view (b) typical plan view of the basement floors (c) typical plan view of the superstructure floors.

2.2. Linear Elastic Modeling

Linear elastic models of the representative structure are generated using the analysis software CSI ETABS [11]. In the analysis models, concrete elastic modulus is defined in compliance with Requirements for Design and Construction of Reinforced Concrete Structures (TS 500) [12] and the effective stiffness of the structural members, seismic mass values and damping characteristics are defined in compliance with TBSC 2018 provisions. Considering architectural utilization properties, design live loads are defined in accordance with Design Loads for Buildings (TS 498) [13].

Although stiffness properties of the entire structure are identically defined in all analysis models, response spectrum analysis (RSA) methods provided in the code for strength-based design of buildings with rigid basements requires consideration of three different mass patterns. The TSA requires response spectrum analysis of the entire structure including structural mass characteristics of both the superstructure and the basement (12619 tons in total). On the other hand, the TSLA requires separate response spectrum analyses for the superstructure (7988 tons) and the basement (4631 tons), separately. Based on these mass patterns, natural vibration periods and corresponding modal mass participation ratios are presented in Table 1 for each mode of vibration of the structure, for all three analysis approaches. Note that in this table, mass participation of the first mode in free vibration analysis of the superstructure is less than the second and third modes due to effect of torsional behavior on the first mode of the structural system. Furthermore, in order to satisfy the required total effective model mass participation ratio of 95% in each direction in TBSC 2018 for RSA, the first 35 vibration modes of the total structure, the first 11 modes of the superstructure, and the first 60 modes of the basement levels are considered in the analyses.

Table 1 - Fundamental vibration periods and corresponding mass participation ratios of the total structure, superstructure, and basement substructure

Total Structure Mass							
Mode Number	Period (s)	X Direction Mass Participation Ratio	Y Direction Mass Participation Ratio	R_Z Direction Mass Participation Ratio	ΣX	ΣY	ΣR_Z
1	1.472	0.000	0.179	0.258	0.000	0.179	0.258
2	1.243	0.000	0.337	0.109	0.000	0.516	0.368
3	1.009	0.508	0.000	0.013	0.508	0.516	0.380
4	0.402	0.000	0.029	0.053	0.508	0.545	0.434
…	…	…	…	…	…	…	…
34	0.037	0.000	0.002	0.000	0.950	0.963	0.890
35	0.036	0.007	0.005	0.003	0.957	0.963	0.893

Superstructure Mass Only							
Mode Number	Period (s)	X Direction Mass Participation Ratio	Y Direction Mass Participation Ratio	R_Z Direction Mass Participation Ratio	ΣX	ΣY	ΣR_Z
1	1.472	0.000	0.273	0.534	0.000	0.273	0.534
2	1.243	0.000	0.513	0.225	0.000	0.786	0.759
3	1.009	0.774	0.000	0.027	0.774	0.786	0.786
4	0.402	0.000	0.037	0.106	0.774	0.823	0.892
…	…	…	…	…	…	…	…
10	0.103	0.003	0.000	0.001	0.986	0.983	0.984
11	0.095	0.000	0.000	0.004	0.986	0.983	0.988

Basement Mass Only							
Mode Number	Period (s)	X Direction Mass Participation Ratio	Y Direction Mass Participation Ratio	R_Z Direction Mass Participation Ratio	ΣX	ΣY	ΣR_Z
1	0.099	0.005	0.749	0.001	0.005	0.749	0.001
2	0.083	0.769	0.007	0.077	0.775	0.756	0.078
3	0.059	0.000	0.039	0.030	0.775	0.795	0.108
…	…	…	…	…	…	…	…
59	0.019	0.001	0.000	0.001	0.953	0.950	0.952
60	0.019	0.000	0.000	0.000	0.953	0.951	0.952

2.3. Nonlinear Modeling

A nonlinear analysis model for the structure (Figure 2) is generated using the commonly-used nonlinear analysis software CSI Perform3D [14]. In compliance with TBSC 2018 provisions on nonlinear modeling of structures, nonlinear flexural behavior of beams and columns are modeled using the lumped plasticity (plastic hinge) approach (Figure 3).

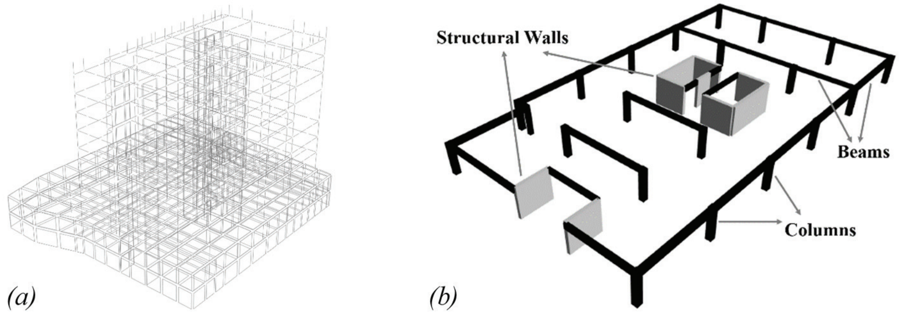


Figure 2 - Nonlinear model of the building; (a) model geometry (b) nonlinear structural elements.

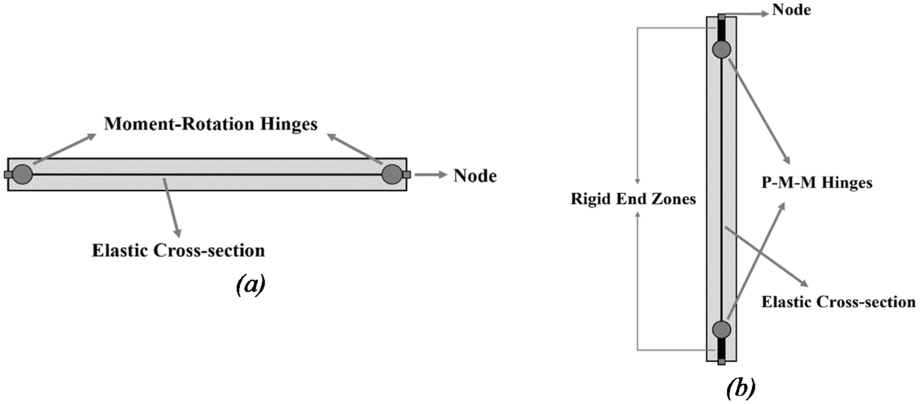
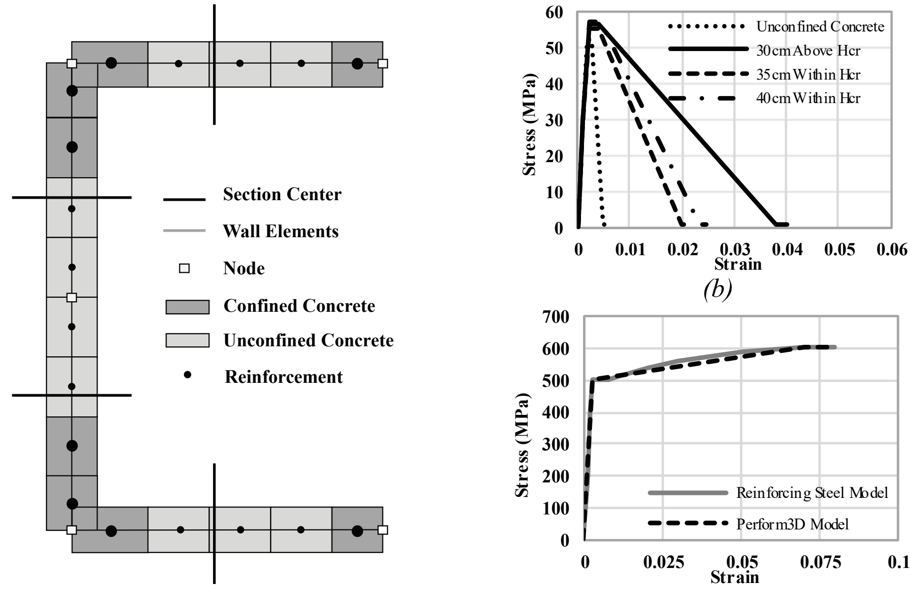


Figure 3 - Modeling of frame elements with lumped plasticity in Perform3D; (a) beams (b) columns.

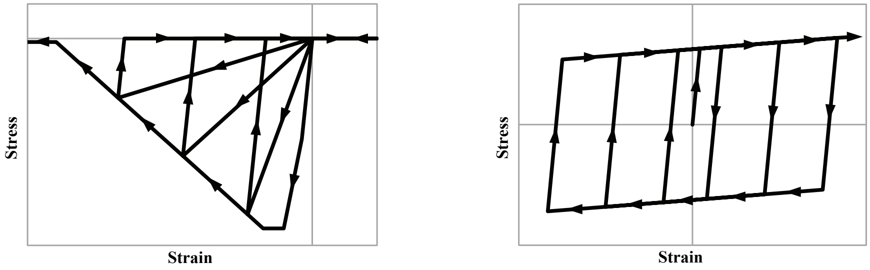
On the other hand, distributed plasticity (fiber modeling) approach is utilized to simulate the nonlinear flexural behavior of the structural walls, by assigning fiber cross-sections (taking into account the different confinement characteristics of boundary regions within and above the critical height) shown in Figure 4 to each wall model element along the entire height of the structure. The floor slab at the transfer floor level and the perimeter basement walls are included in the analysis model assuming linear elastic behavior employing effective stiffness modifiers in TBSC 2018. Floor slabs at the superstructure levels are not included in the model, and their in-plane stiffness is represented assuming a rigid diaphragm constraint.



(a) (b) (c)

Figure 4 - Modeling of structural walls with the distributed plasticity (fiber modeling) approach in Perform3D: (a) fiber discretization of the wall cross-section (b) concrete stress-strain backbone curves (c) reinforcement stress-strain backbone curve

In the nonlinear model, the expected compressive strength of concrete is defined as fce=52 MPa and the expected yield strength of reinforcing steel is defined as fye=504 MPa, in compliance with TBSC 2018 provisions. For simplicity, cyclic stiffness degradation is neglected in definition of material hysteretic behavior, and the hysteretic rules illustrated in Figure 5 are adopted during generation of the analysis model.



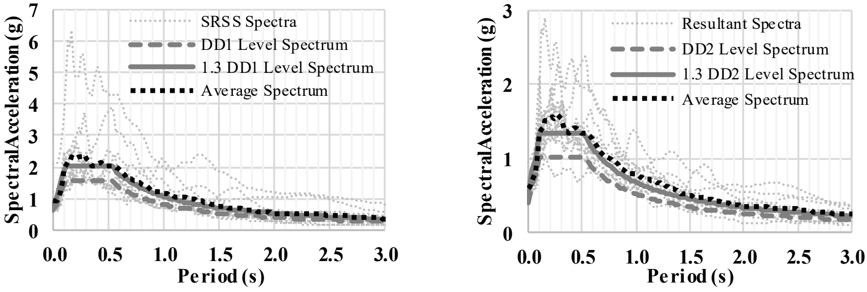
(a) (b)

Figure 5 - Hysteretic rules adopted for material stress-strain behavior: (a) concrete (b) reinforcement.

In addition to the inelastic energy dissipation (hysteretic damping) due to explicit modeling of the hysteretic behavior of the structural members, an additional 5.0% equivalent viscous damping is introduced in the nonlinear analysis model, as a combination of 4.9% modal damping and 0.1% Rayleigh damping, as recommended by Powell [15]. Detailed information on generation of both the linear elastic models and the nonlinear model of the structure is presented in the thesis by Abediasl [16].

2.4. Seismic Hazard Definition and Ground Motion Record Selection and Scaling

The building structure is analyzed under the so-called DD1 and DD2 level ground motion levels defined in TBSC 2018, where DD1 corresponds to the maximum credible earthquake with a probability of exceedance of 2% in 50 years (2475 years recurrence period), and DD2 corresponds to the design level earthquake with a probability of exceedance of 10% in 50 years (475 years recurrence period). Spectral parameters defined for the building site location are used to generate the design spectra, in accordance with the Turkish Earthquake Hazard Map [17]. The design spectra shown in Figure 6 are generated for the DD1 and DD2 ground motion levels and the local soil conditions at the building site, where the local soil class is considered to be ZB ($760<V_{s,30}<1500$m/s).



(a) *(b)*

Figure 6 - SRSS acceleration response spectra of selected ground motions for ground motion levels: (a) DD1 (b) DD2.

For nonlinear response history analyses, selection and scaling of 22 pairs of ground motions (11 pairs per each earthquake level) is conducted using the NGAWest2 Ground Motion Database [18], employing amplitude scaling and by matching the SRSS resultant spectra of the ground motion components with a target spectrum, which is defined as 1.3 times (since the spectrum is defined in terms of geometric mean of the components) the code spectrum, for DD1 and DD2 level earthquakes, as described in TBSC 2018 (Figure 6). Details on selection and scaling of the ground motion records are provided in the thesis by Abediasl [16].

2.5. Code-Specified Analysis Methods for Strength-Based Design

In TBSC 2018, a building structure is classified as incorporating a laterally-rigid basement when the basement is surrounded by perimeter walls along at least three sides, and when the difference between fundamental vibration periods obtained from free vibration analysis considering the total mass of the structure vs. the mass of only the superstructure not exceeding 10% in both directions. In other words, when the ratio of the fundamental vibration period of the total structural system divided by that of only the superstructure (considering superstructure mass only) is less than 1.1, the structure is classified to have a rigid basement. In the code, one of four alternative analysis methods is allowed for strength-based design of buildings with rigid basement floors. These four alternative methods, which are applications of the equivalent lateral force analysis (ELFA) method or the response spectrum analysis (RSA) method, using the total structure approach (TSA) or the two-stage loading approach (TSLA), are described in relevant sections of TBSC 2018 as listed in Table 2.

Table 2 - Alternative linear elastic analysis methods specified in TBSC 2018 for buildings with rigid basements.

	ELFA Method	RSA Method
Total Structure Approach (TSA)	Section 4.3.6.1	Section 4.3.6.2
Two-Stage Loading Approach (TSLA)	Section 4.7.5	Section 4.8.5

RSA methods are applicable for strength-based design of buildings with any structural configuration, but applicability of the ELFA methods is dependent on the building height criteria and the structural irregularity characteristics specified in the code. Procedures of all methods require definitions for structural system behavior factor (R), overstrength factor (D) and building importance factor (I) for both the superstructure and the basement levels. Since the governing lateral-load-resisting structural system of the investigated building in both directions is considered as uncoupled structural walls, and the structure is designed as a residential building, the structural system behavior factor is defined as $R=6.0$. The structural system overstrength factor is defined as D=2.5, and the building importance factor is defined as I=1.0 for the superstructure. On the other hand, as per TBSC 2018 provisions, the ratio of structural system behavior factor to the building importance factor is defined as R/I=2.5, and the system overstrength factor is defined as D=1.5 for the basement levels.

2.5.1. Analysis Methods Using the Total Structure Approach (TSA)

In the total structure approach (TSA) for modeling/analysis, a single model of the building that represents the stiffness and mass characteristics of the entire structure (basement and superstructure) is generated. In accordance with Section 4.3.6.1 of TBSC 2018, seismic demands on the upper superstructure are obtained with application of the ELFA method, using the factors defined for the superstructure (R=6.0, D=2.5, I=1.0). In the ELFA method, the fundamental assumption is that dynamic response of the structure is dominated by the first mode of vibration, and earthquake loads can be defined using the conventional inverse triangle earthquake load distribution (proportional to the product of story mass and story elevation) along the building height, measured from ground level to the roof elevation of the buildings. Although the inverse triangle load distribution must be applied starting from top of the basement floors in the conventional definition of ELFA method, when the method is applied to buildings with rigid basements using the total structure approach, the linear elastic earthquake load distribution is applied starting from the base of the entire structure (foundation level), neglecting the stiffness irregularity between the superstructure and the rigid basement structure of the building (Figure 7), and the design-basis (reduced) earthquake loads obtained in the superstructure are then obtained as shown in Figure 8a. For the basement levels, according to Section 4.3.6.1, explicit calculations for a specific seismic load reduction factor ($(\bar{R}_a)^{(X)}_{lower}$) and a specific overstrength factor ($\bar{D}^{(X)}_{lower}$) are required. These specific factors are calculated considering the linear elastic earthquake load distribution along the height of the entire structure (using the resulting base shear force values developing at the base of the superstructure and at the base of the basement structure) (Figure 7), together with the seismic load reduction factors (R_a) calculated using the factors defined for superstructure (R=6.0, D=2.5, I=1.0) and the basement levels (R/I=2.5, D=1.5), as defined in Equations (1)-(3).

$$v^{(X)}_{upper} = \frac{V^{(X)}_{x,upper}}{V^{(X)}_{x,total}} \; ; \; v^{(X)}_{lower} = (1 - v^{(X)}_{upper}) \frac{(R_a)^{(X)}_{upper}}{(R_a)^{(X)}_{lower}} \; ; \; v^{(X)} = v^{(X)}_{upper} + v^{(X)}_{lower} \tag{1}$$

$$(\bar{R}_a)^{(X)}_{lower} = \frac{(R_a)^{(X)}_{upper}}{v^{(X)}} \tag{2}$$

$$\bar{D}^{(X)}_{lower} = \frac{0.6 v^{(X)}_{upper} D_{upper} + v^{(X)}_{lower} D_{lower}}{v^{(X)}} \tag{3}$$

After these explicit calculations, the reduced seismic story shear force demands on the basement levels are obtained by dividing the linear elastic demands by the factor $(\bar{R}_a)^{(X)}_{lower}$ for ductile design (i.e., flexural design, axial/flexural design), and by amplifying the reduced seismic story shear demands with the factor $\bar{D}^{(X)}_{lower}$ for design against brittle failure (i.e., shear design, diaphragm design), as shown in Figure 8b.

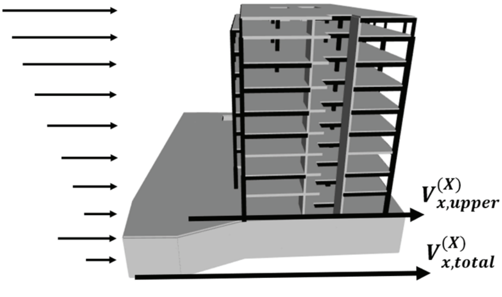
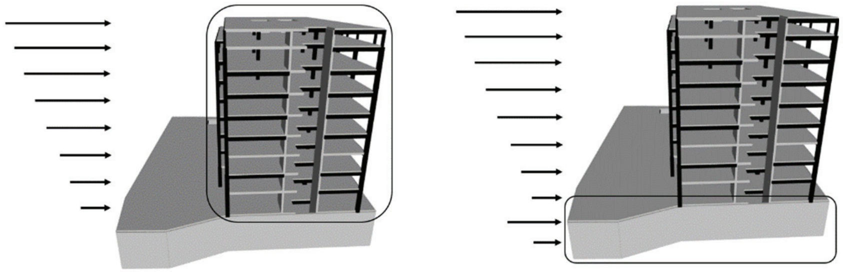


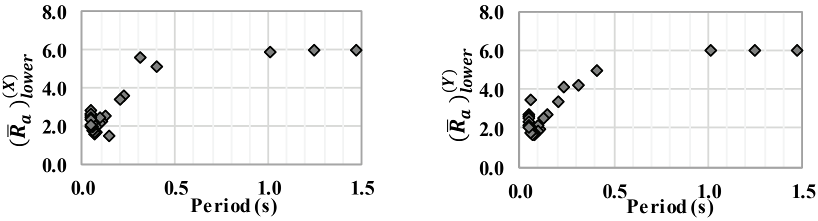
Figure 7 - Linear elastic earthquake load distribution for calculation of $(\bar{R}_a)^{(X)}_{lower}$ *and* $\bar{D}^{(X)}_{lower}$.



(a) R=6.0, D=2.5 *(b)* $(\bar{R}_a)_{lower}$, $\bar{D}^{(X)}_{lower}$

Figure 8 - Design-basis seismic demands based on Section 4.3.6.1; (a) on superstructure floors (b) on basement floors.

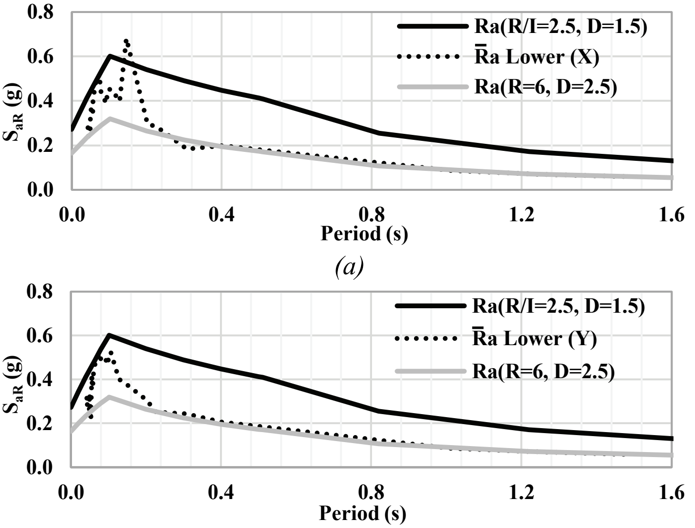
TBSC 2018 does not allow application of ELFA if the superstructure height exceeds 42 m. With presence of significant torsional irregularity or soft story irregularity, the height limit for applicability of ELFA reduces to 28m. Structures with rigid basement floors that do not satisfy these criteria can be designed using RSA with total structure approach (TSA) in accordance with Section 4.3.6.2. For design of the superstructure, seismic demands are obtained by calculation of reduced earthquake loads considering factors defined for the superstructure (*R*=6, *D*=2.5, *I*=1.0). However, in design of the basement, calculation of specific seismic load reduction factors, $(\bar{R}_a)^{(X)}_{n,lower}$, and overstrength factors, $\bar{D}^{(X)}_{n,lower}$, corresponding to each vibration mode is required. In order to calculate these factors for each vibration mode using Equations (1)-(3), base shear values (at the base of the superstructure and at the foundation level) for all vibration modes considered in RSA are necessary. Even though the software CSI ETABS does not provide decomposed internal shear force contributions for individual vibration modes in RSA, shear force distributions based on modal effective masses can be obtained from free vibration (modal) analysis and can be used in the calculations, as permitted in the code. First, for the X direction, using these shear force distributions of individual vibration modes, required base shear ratios ($v^{(X)}_{upper}$ and $v^{(X)}_{lower}$) for calculation of $v^{(X)}$ and corresponding $(\bar{R}_a)^{(X)}_{n,lower}$ and $\bar{D}^{(X)}_{n,lower}$ of each mode (including the modes in Y direction) were obtained, and then, calculations were repeated for the factors to be used in Y direction. The reason for consideration of all modes in calculations is the possible directionally uncoupled vibration modes that can be encountered in more complex structural systems. In Figure 9, seismic load reduction factors calculated using this approach, for all modes of vibration of the building in both directions, are illustrated.



(a) *(b)*

Figure 9 - Seismic load reduction factors for the basement calculated for all modes of vibration in (a) X-direction (b) Y-direction.

TBSC 2018 also provides an alternative simplified approach, where instead of explicitly calculating specific seismic load reduction factors and overstrength factors for each vibration mode, reduced seismic demands can be obtained using values of R/I=2.5 and D=1.5 assumed for the basement structure, as described in Section 4.3.6.2(b). Comparison of the reduced (ductile) design spectra for the DD2 level ground motion, using factors defined for superstructure (R=6.0, D=2.5, I=1.0), as well as the modal load reduction factors calculated for the basement floors ($((\bar{R}_a)^{(X)}_{n,lower})$) and the simplified method for the basement floors (R/I=2.5, D=1.5) is presented in Figure 10, for both directions of the building investigated.



(a)

(b)

Figure 10 - Reduced (ductile) design spectra for the superstructure and the basement structure of the building in: (a) X-direction (b) Y-direction.

2.5.2. Analysis Methods Using the Two Stage Loading Approach (TSLA)

According to TBSC 2018, alternatively to the total structure approach (TSA), the two-stage loading approach (TSLA) can also be utilized in design of the rigid basement levels. In the two-stage analysis approach, two separate models of the structure are generated, such that both models represent the stiffness characteristics of the entire structure (basement and superstructure), but one model includes only the mass of the superstructure whereas the other model includes only the mass of the basement. In accordance with Section 4.7.5, in design of the superstructure using ELFA method, design (reduced) earthquake loads are calculated using factors R=6.0, D=2.5 and I=1.0 and taking only the superstructure mass into consideration in analysis. Seismic demands obtained from this first stage of analysis are used for design of the upper superstructure (Figure 11a). For design of the basement levels, as a second stage of analysis, linear elastic earthquake loads acting on the basement floors are calculated by multiplication of basement floor masses with the design spectral acceleration corresponding to zero period of vibration (effective peak ground acceleration). Then, the design (reduced) earthquake loads are calculated using factors R/I=2.5 and D=1.5. In order to obtain design-basis internal forces on the basement levels, seismic demands from first and second stages of analysis are superimposed (Figure 11b), as described in Section 4.10 of TBSC 2018. Note that this analysis method specified in Section 4.7.5 of the TBSC 2018 is similar to the approach prescribed in the previous Turkish Seismic Code (TSC 2007) [19]. Differently from the previous code, TBSC 2018 also permits application of Section 4.8.5, where the RSA method can be used in analysis of the basement structure as well.

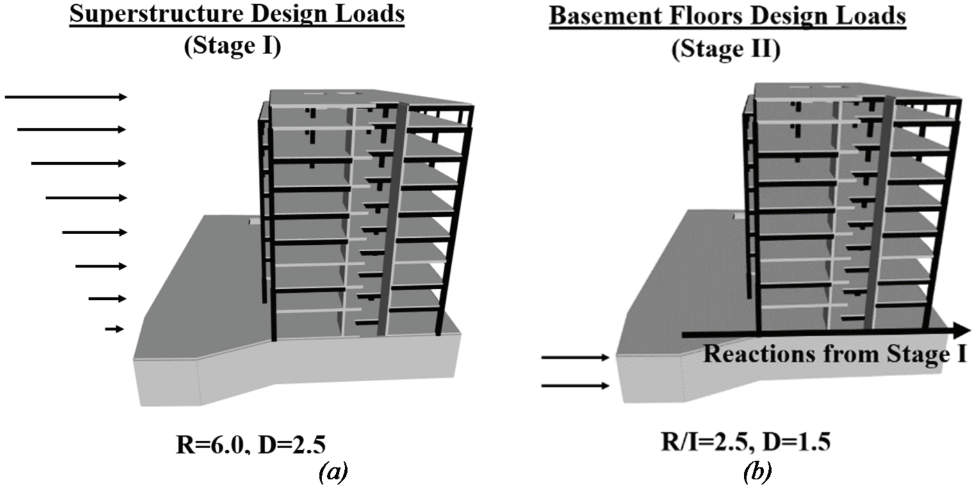


Figure 11 - Calculation of design loads based on Section 4.7.5; (a) superstructure (b) basement floors.

In accordance with Section 4.8.5 of TBSC 2018, during the first stage of analysis, response spectrum analysis can be conducted using factors defined for the superstructure ($R=6.0$, $D=2.5$, $I=1.0$), where only the superstructure mass is considered. Design (reduced) internal forces on the superstructure are obtained from the results of this first stage of analysis. During the second stage of analysis, reduced seismic demands on the basement levels can be obtained also using response spectrum analysis, using the relevant factors defined for basement levels ($R/I=2.5$, $D=1.5$), and taking only the basement mass into account. Similar to the procedure defined for Section 4.7.5, the total design-basis seismic demands on the basement levels are obtained by superposition of analysis results obtained for the first and the second stages of analysis, as described in Section 4.10 of TBSC 2018.

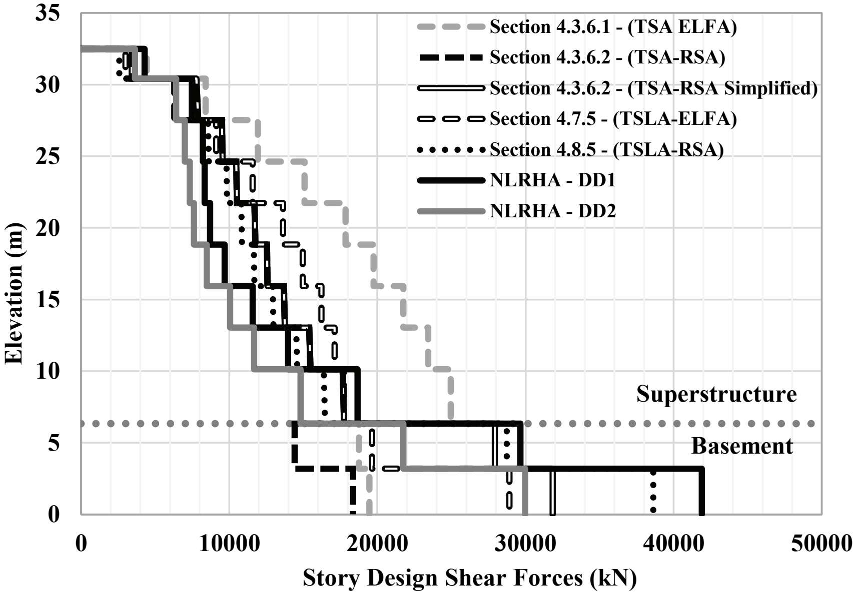
3. ANALYSIS RESULTS

In order to evaluate the consistency and the reliability (or conservatism) of the alternative analysis methods prescribed in TBSC 2018 for design of structures with rigid basements, design-basis shear force demands (story shear forces and internal shear forces on structural walls) obtained using the alternative linear elastic analysis methods are compared with nonlinear response history analysis results. For all linear elastic analyses, design-level (DD2) code spectrum is used, as specified in TBSC 2018. For NLRHA, 11 pairs of ground motion records are selected and scaled to match design spectra corresponding to DD2 (design-level) and DD1 (maximum considered) ground motion levels. It must be noted that direct comparison of DD1-level NLRHA results with DD2-level design-basis linear elastic analysis results (that consider load reduction and overstrength factors) is not a consistent comparison. Nevertheless, DD1-level NLRHA results are also presented for the readers' information, since TBSC 2018 (as well as other seismic codes) implicitly target that strength-based design of a low- or medium-rise structure under the design-level (DD2) seismic hazard will satisfy collapse prevention performance under the maximum considered (DD1) seismic hazard level. When expected (vs. design) material strengths are considered in member (section) capacity calculations, and also considering the inherent conservatism embedded in code-defined capacity (ultimate strength) equations as well as the conservatism embedded in code-prescribed member/system ductility characteristics (e.g., in the structural behavior factor, *R*). A total of 22 analyses are conducted for NLRHA under each hazard level, first by applying 11 ground motion record pairs, and secondly by re-applying the records at a 90-degree-rotated state. The mean of the maximum shear force demands obtained from the 22 analyses are used for comparisons with design-basis linear elastic analysis results (that incorporate load reduction and overstrength coefficients). Within the scope of the comparisons, first, design-basis story shear force demands that are obtained by amplifying the results of the alternative linear elastic analysis methods discussed in Section 2 of this paper by corresponding system overstrength factors (*D*), are compared with NLRHA results obtained for story shear forces. Secondly, shear force demands on selected structural walls obtained by amplifying the linear elastic analysis results by a factor *1.2D* (as specified in TBSC 2018, since dynamic amplification and flexural overstrength effects are expected to be more significant for the structural walls, compared to the entire structural system) are compared with NLRHA results obtained for structural wall shear forces. The reason that only shear force (story shear force and wall shear force) demands are considered in the comparisons is because shear is considered as a force-controlled (i.e., brittle) action in both design and performance assessment, and therefore shear demands obtained from results of design-basis linear elastic analysis (considering load reduction and overstrength factors) and nonlinear dynamic analysis (NLRHA) are equally-relevant, in terms of design against shear. It is also important to note that analysis results as well as the relevant outcomes are naturally sensitive to the modeling assumptions (e.g., modeling of structural walls with fiber elements, representation of transfer floors with linear elastic shell elements etc.) adopted during generation of analysis models. Further details on the overall nonlinear dynamic behavior, ductility characteristics, and seismic performance of the structure are provided in the thesis by Abediasl [16].

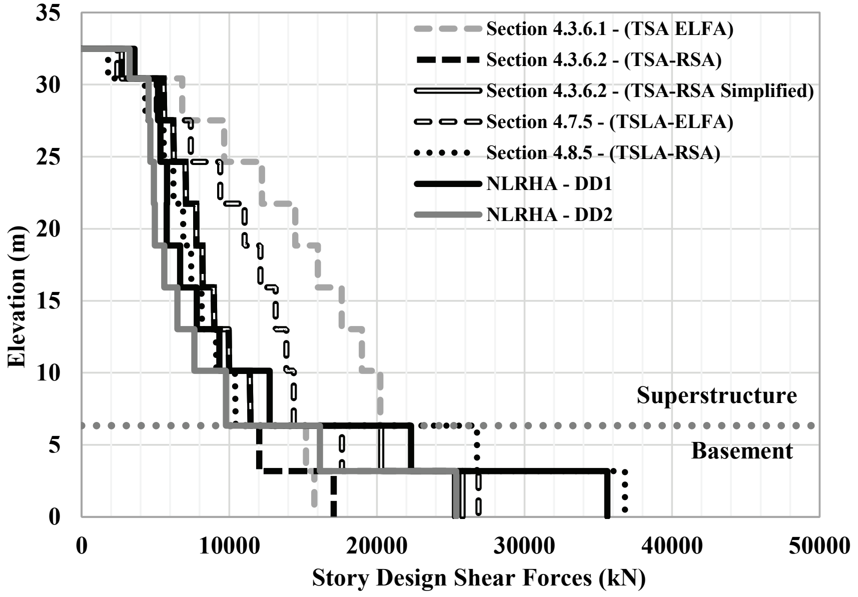
3.1. Story Shear Forces

Design-basis story shear force demands obtained using the four alternative linear elastic analysis methods are compared with NLRHA results in Figure 12. When the design-basis story shear force demands on the superstructure are compared with NLRHA results, it is observed that all analysis methods except ELFA with TSA (Section 4.3.6.1) gives reasonable story shear force distributions along the height of the building investigated. The reason for the overly-conservative (too large) story shear force demands developing on the superstructure obtained using ELFA with the TSA is because in this approach, story-mass and story-elevation-proportional earthquake load distribution is applied starting from foundation level of the building, instead of the ground level, when the total structure approach (TSA) is adopted. In this approach, since the basement masses are also considered in the distribution of the equivalent static earthquake forces, story shear force demands on the superstructure are overestimated, compared to DD-2 level NLRHA results. In general, the story shear force demands obtained for the superstructure using the other three alternative methods of analysis are reasonable, and are either slightly on the conservative side (when RSA is used) or moderately on the conservative side (when ELFA is used), compared to NLRHA results obtained under DD2-level (design-level) ground motion, as illustrated in Figure 12.

On the other hand, significant scatter/inconsistency between the design-basis story shear force demands obtained using the alternative analysis methods is observed along the basement stories of the building, as shown in Figure 12. ELFA and RSA with the TSA provide unreasonably-low story shear force demands, due to the high values calculated using Equations (1) and (2) for the seismic load reduction factor to be used in design of basement structure (i.e., $(\bar{R}_a)_{lower}$), especially at longer vibration periods for which the superstructure is more dominantly excited (Figure 9). However, the simplified approach that involves RSA with the TSA in Section 4.3.6.2(b), where the modal seismic load reduction factors for the basement structure are not explicitly calculated and the seismic demands are obtained by simply assuming R/I=2.5 and D=1.5 for the basement structure, provides story shear force demands that are in much better agreement with NLRHA results under the DD2 level ground motion. Furthermore, ELFA with the TSLA described in Section 4.7.5 provides the closest story shear force values to DD2-level NLRHA results, whereas RSA with the TSLA described in Section 4.8.5 predicts unreasonably high story shear force demands that almost reach DD1-level NLRHA results. Separate RSA of the basement structure conducted during the second stage of TSLA yields too large shear force demands (compared to NLRHA results), since the predominant vibration periods of the basement structure fall in the maximum-spectral-acceleration region of the design spectrum, for which the basement is subjected to highest spectral accelerations. However, it is important to note that the building structure investigated in this study incorporates only two basement levels. Taller (i.e., multi-story) basements would inherently be more flexible (with higher vibration periods); and therefore, RSA of the basement applied during the second stage of the TSLA approach may provide more realistic seismic demands on the multi-story basements of such buildings. Furthermore, for buildings with superstructures that are not eligible (i.e., too tall or too irregular) for application of the ELFA, one viable approach may be combination of the first stage of analysis described in Section 4.8.5 (RSA for the superstructure) with second stage of analysis described in Section 4.7.5 (ELFA for the basement, assuming constant spectral acceleration corresponding to zero vibration period on all basement floors), similarly to the approach prescribed in the previous version of the Turkish Seismic Code (TSC 2007). For the building investigated, the level of accuracy of all of the alternative code-recommended methods of linear elastic analysis are summarized in Table 3. In the table, the relative differences between the story shear force demands obtained using the alternative linear elastic analysis methods and those obtained using NLRHA under the DD2-level ground motion are provided, at the base of superstructure (i.e., at ground level) and at the bottom elevation of the basement (i.e., at foundation level). The values provided in the table are obtained first calculating the difference between story shear demands obtained from nonlinear and linear



(a)



(b)

Figure 12 - Comparison of story shear force demands obtained using linear elastic (design-basis) and nonlinear analysis methods in (a) X-direction (b)Y-direction.

analyses (nonlinear analysis result – linear analysis result), then dividing this difference to the nonlinear analysis result (e.g., +20% correspond to the case where story shear force from linear analysis is equal to 120% of the value obtained from nonlinear analysis). Based on the analysis results presented in Figure 12 and Table 3, for obtaining design-basis story shear force demands developing along the basement stories of the building investigated, the simplified approach (assuming R/I=2.5 and D=1.5 for the basement) using RSA with the TSA described in Section 4.3.6.2(b), and ELFA with the TSLA described in Section 4.7.5 are clearly identified as the more accurate analysis approaches in replicating the NLRHA results. On the other hand, along the stories of the superstructure of the building, RSA with the TSLA approach provides design-basis story shear forces that most closely match the NLRHA results.

Table 3 - Comparison of design-basis story shear force demands obtained using TBSC 2018 linear elastic analysis methods with NLRHA results under DD2 ground motion level

Analysis Approach	**Analysis Type**	**Analysis Method (Section)**	**Relative to NLRHA-DD2 (Story Shear Forces)**	
			Superstructure	**Basement**
TSA	ELFA	4.3.6.1	+70% (X) +105% (Y)	-35% (X) -40% (Y)
TSA	RSA	4.3.6.2	+20% (X) +20% (Y)	-40% (X) -35% (Y)
TSA	RSA	Simplified 4.3.6.2(b)	+20% (X) +20% (Y)	+5% (X) +0% (Y)
TSLA	ELFA	4.7.5	+20% (X) +50% (Y)	-5% (X) +5% (Y)
TSLA	RSA	4.8.5	+10% (X) +5% (Y)	+30% (X) +45% (Y)

3.2. Structural Wall Shear Forces

Design-basis shear force demands developing on the C-shaped structural walls (PC01 and PC02 in Figure 1c), which were obtained using the linear elastic analysis methods that were shown in the previous section to be more accurate in replicating the story shear force distributions obtained from nonlinear analysis (the TSLA-ELFA approach described in Section 4.7.5 and the simplified TSA-RSA approach described in Section 4.3.6.2(b) of TBSC 2018), are compared herein with NLRHA results under DD1 and DD2-level ground motions, as shown in Figures 13 and 14 (in the X direction of the building) and Figures 15 and 16 (in the Y direction of the building). From the wall shear force distributions depicted in these figures, it is observed that both methods provide reasonable design-basis wall shear force demands developing along the height of the superstructure (compared to DD2-level NLRHA results), although ELFA results are occasionally more conservative compared to RSA results (e.g., Figures 15 and 16), as expected. On the other hand, due to the so-called backstay effects [20], which were observed in the analysis results at the transfer floor (where the shear forces on the structural walls are transferred to perimeter basement walls by the diaphragm), the TSLA-ELFA approach described in Section 4.7.5 largely underestimates the shear force demands developing on the structural walls along the basement stories of the building. When this approach is used, during the first stage of analysis, when the equivalent static lateral forces are applied to the superstructure, the shear force demands obtained along the height of the basement are found to be in the opposite direction to those developing in the superstructure. Subsequently, algebraic addition of the wall shear force demands obtained from the first (superstructure) and second (basement) analysis stages (which are in opposite directions), partially cancel out each other and may lead to unreasonably small total shear force demands obtained along the basement stories of the building (e.g., see Figures 14-16), which may be misleading to design engineers. Although this effect is not as pronounced in the simplified TSA-RSA approach described in Section 4.3.6.2(b) of TBSC 2018 (since modal superposition method is used in RSA), analysis results indicate that wall shear force demands obtained using this approach may still occasionally be lower compared to NLRHA

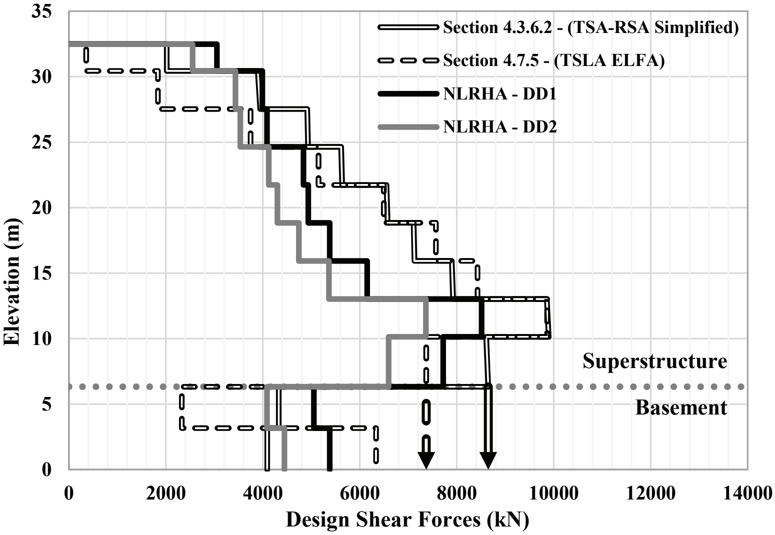


Figure 13 - Comparison of shear force demands on structural wall PC01 in X direction.

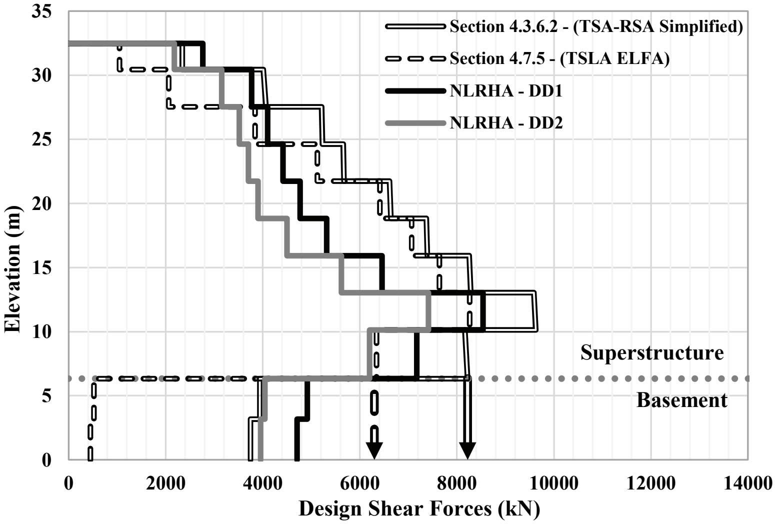


Figure 14 - Comparison of shear force demands on structural wall PC02 in X direction.

results obtained under DD2 level ground motion (e.g., see Figure 15). Since neither of these two analysis approaches provide consistently reliable estimations of wall shear force demands developing along the basement stories of the building investigated, a design-basis minimum wall shear force criterion is recommended in this study for buildings with rigid basements, where the design-basis wall shear force shall not be taken smaller than the that obtained at base of the wall (i.e., at ground level), along a depth corresponding to at least two basement story heights (or possibly larger), as illustrated in Figures 13-16 using downward arrows.

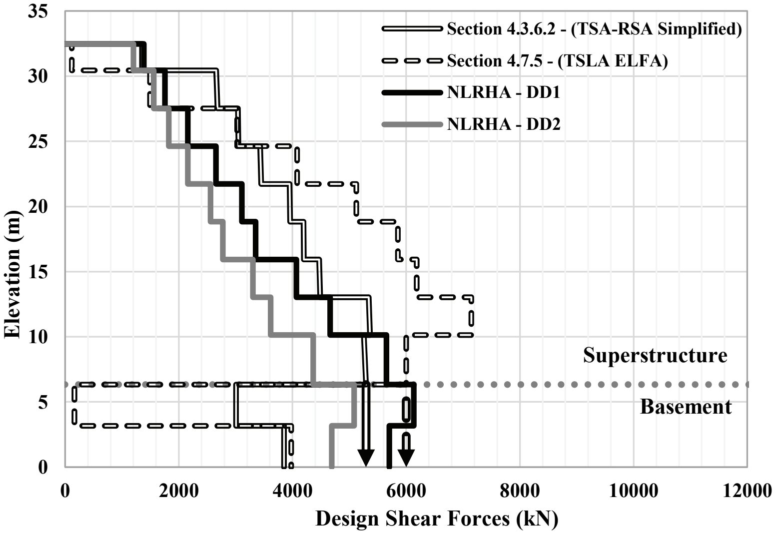


Figure 15 - Comparison of shear force demands on structural wall PC01 in Y direction.

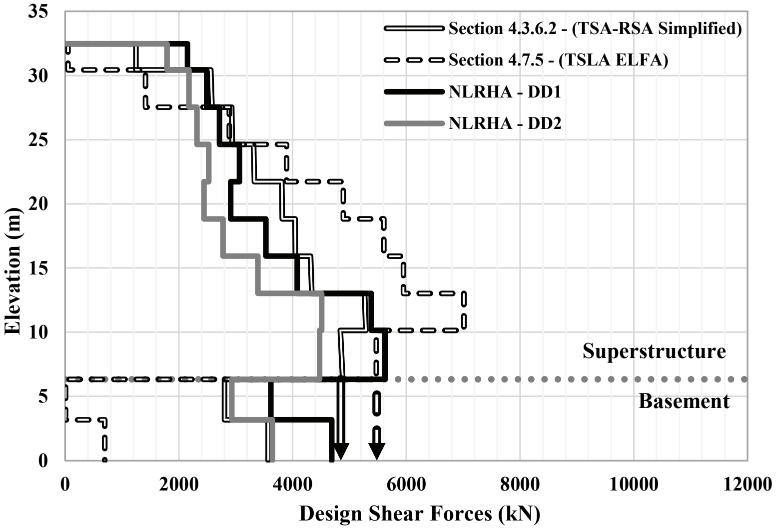


Figure 16 - Comparison of shear force demands on structural wall PC02 in Y direction.

4. CONCLUSIONS

In light of the analysis results presented in this study for the representative reinforced concrete building structure investigated, the following conclusions are derived on the effectiveness of the alternative modeling and analysis approaches prescribed in the 2018 Turkish Building Seismic Code for analysis of buildings with laterally-rigid basement levels:

- Seismic shear demands obtained using some of the alternative analysis methods specified in TBSC 2018 for the rigid basement levels of building structures incorporate uncertainties and difficulties in application. As well, analysis results obtained using the analysis methods may show significant variability when compared with each other.

- The equivalent lateral force analysis (ELFA) method using the total structure approach (TSA) described in Section 4.3.6.1 of TBSC 2018 leads to overestimated story shear force demands on the superstructure, due to negligence of the significant difference between the lateral stiffness of the superstructure and the rigid basement. Furthermore, the method underestimates the story shear force demands developing along the basement stories, due to an unreasonably high seismic load reduction factor ($(\bar{R}_a)_{lower}$) value calculated for the basement, which is close to that of the superstructure. Application of the equivalent lateral force analysis (ELFA) method with the total structure approach (TSA) is not recommended for analysis of buildings with rigid basements.

- Similarly, modal seismic load reduction factor ($(\bar{R}_a)_{n,lower}$) calculations to be used in response spectrum analysis (RSA) using the total structure approach (TSA) described in Section 4.3.6.2 are tedious and do not necessarily generate a rational design (reduced) spectrum to be used in the analysis of the basement structure. When this approach is used, the modal seismic load reduction factors calculated for the basement of the building investigated (corresponding to vibration modes that excite the basement) are found to be close to those of the superstructure (modes with higher vibration period). The TSA approach (used in both RSA and ELFA) is deemed more suitable for structural systems in which the upper and the lower components of the system have closer behavior coefficients (ductility and overstrength characteristics) and therefore closer load reduction factors. However, using the simplified approach recommended in Section 4.3.6.2 (using R/I=2.5 and D=1.5 for the basement) provides story shear force demands that are reasonably close to NLRHA results obtained under the design-level (DD-2 level) ground motion. It is recommended that when conducting RSA using the TSA, modal seismic load reduction factors be not explicitly calculated for the basement, and only the simplified version of the TSA-RSA approach (Section 4.3.6.2(b)) be adopted for analysis of laterally-rigid basements. Besides, since this approach does not require neither additional calculations for seismic load reduction factors nor combination of analysis results from different loading stages, it can be deemed as the most practical approach among the others.

- As far as the story shear force demands developing along the rigid basement stories of a building are considered, the equivalent lateral force analysis (ELFA) method with the two-stage loading approach (TSLA) described in Section 4.7.5 of TBSC 2018 is found to be a reliable analysis method to be applied along the basement stories of low- or medium-rise buildings, for which the application of equivalent lateral force analysis method is permitted for the superstructure. However, when significant backstay effects are observed in the analysis results, erroneous application of this method may lead to significant overestimation of shear force demands developing on the structural walls along the basement stories.

- Application of response spectrum analysis (RSA) using the two stage loading approach (TSLA) described in Section 4.8.5 of TBSC 2018 provides story shear force demands on the superstructure that best replicate NLRHA results, but may result in overestimation of story shear force demands developing along the rigid basement stories. This is because the predominant vibration periods of the basement structure may potentially fall in the maximum-spectral-acceleration region of the design spectrum (as opposed to the TSLA-ELFA method, for example, in which the spectral acceleration of the basement structure is assumed to correspond to zero period of vibration). However, this may differ for buildings with relatively flexible (e.g., multi-story) basement structures, and the TSLA-RSA method may be more representative of NLRHA results for such buildings. Furthermore, in analysis of buildings for which ELFA is not permitted for the superstructure, one option may be to apply RSA for the superstructure during the first stage of analysis using the TSLA, and to apply ELFA for the rigid basement during the second stage of analysis, similarly to the approach prescribed in the previous version of the Turkish Seismic Code [19].
- Since none of the alternative analysis methods is found to provide reliable estimations of the shear force demands developing on the structural walls along the basement stories of the building investigated (partially due to backstay effects observed in the analysis results of the building), a lower-bound design-basis wall shear force is recommended in this study, where the design-basis shear force on the structural wall shall not be taken smaller than that calculated at base of the wall (at ground level), along a depth equal to at least two basement story heights.

These conclusions were reached upon analysis of a single building structure. Nevertheless, analysis results and their relevance to the code provisions were comparatively discussed, from a mechanics-based viewpoint. The discussions and conclusions presented in this paper are therefore believed to be relevant, although not necessarily general. In order to verify/improve (or possibly disprove) these findings, further numerical investigations on the TBSC 2018 provisions on analysis of buildings with rigid basement levels are recommended, considering various building systems with basements having various other structural configurations.

Notations

D	Structural system overstrength factor
ELFA	Equivalent lateral force analyses
I	Building importance factor
NLRHA	Nonlinear response history analysis
R	Structural system behavior factor
R_a	Seismic load reduction factor

RSA	Response spectrum analysis
TBSC	Turkish Building Seismic Code
TSA	Total structure approach
TSLA	Two stage loading approach

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