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ProtaStructure Design Guide

Seismic Design of Cast-in-Place Concrete Diaphragms to TBDY2018

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Introduction

This guide presents the analysis steps of slab elements in TBDY 2018 (Turkish Seismic Code 2018) Section 7.11 that should be done in ProtaStructure under the influence of earthquakes. Modeling procedures, design requirements, and reporting of results are described in this document. Hints and suggestions are provided for selected seismic codes where necessary.

Elastic and rigid diaphragm definitions can be defined in the versions of ProtaStructure that have been published so far.

Slab Modeling

In structural systems, earthquake loads are transferred to the main structures by the slabs in the floor plane. These slabs can be designed as rigid or semi-rigid (elastic). It is necessary to check that the stresses caused by earthquake loads can be safely carried and transferred to vertical structural members. Although these stress values in beam-and-slab systems are less than in flat slab systems or in the case of significant gaps in the slab, they still need to be checked. Connecting these slabs directly to columns or shear walls is critical as it causes stress concentrations and requires unique controls. For the slab design and post-analysis controls to be carried out correctly, the slab and diaphragm assumptions defined in ProtaStructure must comply with the assumptions specified in TBDY 2018 Section 7.11.

Slab Modeling Recommendations

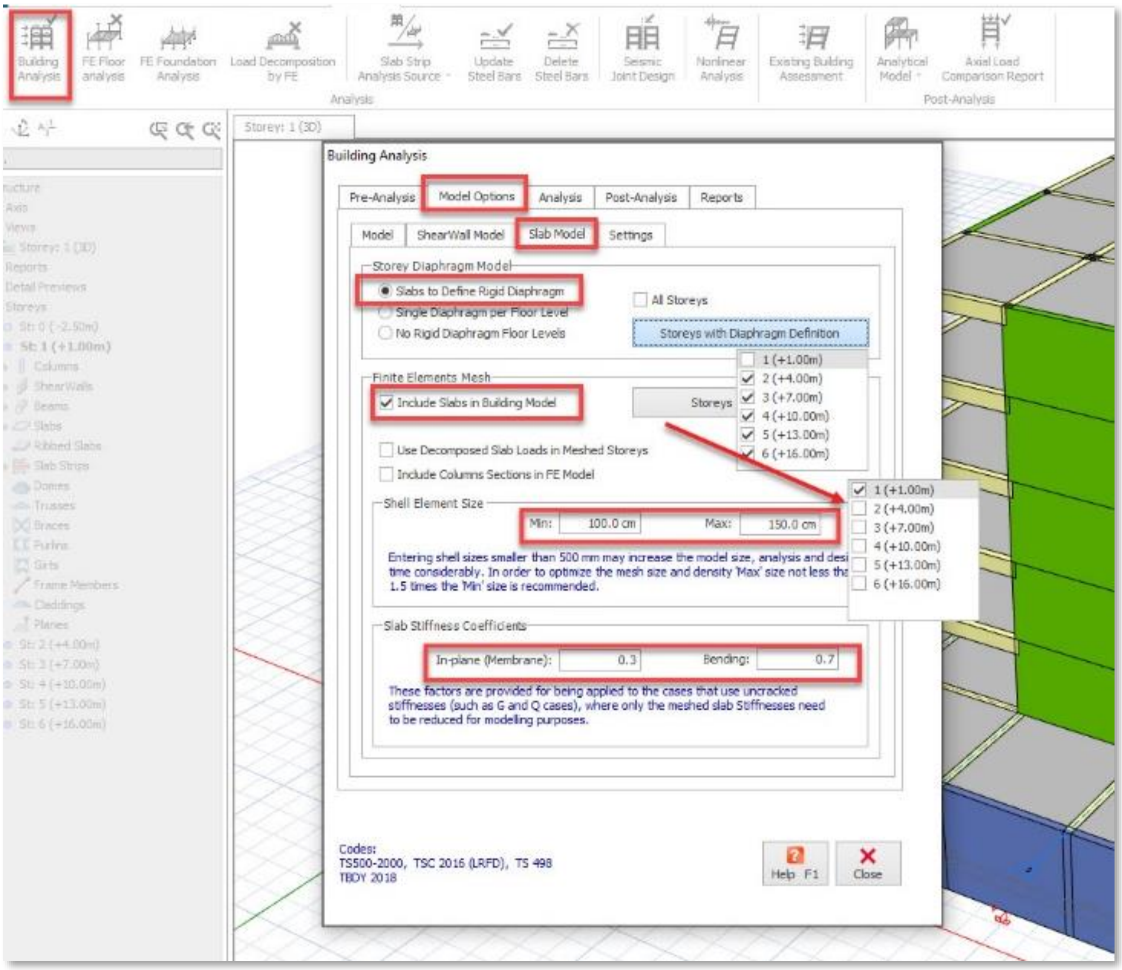
To guide in the creation of valid models, the recommended best practice for pre-analysis and post-analysis checks in ProtaStructure is as follows.

- After the modeling of the structural system is completed, the required slab assumptions can be accessed by clicking on the **Building Analysis > Model Options > Slab Model** tab before proceeding to the building analysis.
- In the **'Slab Model'** tab, there is a section where diaphragm properties, analysis method, mesh size, and slab stiffness ratios can be selected.
    - According to TBDY2018 Section 7.11.5, slabs must be defined as rigid diaphragms to perform post-analysis controls. Depending on the state of the building, ProtaStructure can determine multiple rigid diaphragms or free nodes in a slab (if applicable) by selecting the **'Slabs to Define Rigid Diaphragm'** option in the **'Storey Diaphragm Model'** section. ProtaStructure will automatically decide on rigid diaphragms by examining cases such as disconnected or staggered slabs. Suppose you want to utilize rigid diaphragm assumption only in some storeys. You can choose the floors you want to apply rigid diaphragm constraints using the **'Storey with Diaphragm Definition'** list.
    - As stated in TBDY2018 Section 4.5.6.2, in-plane forces are to be safely transferred to vertical structural members according to TBDY2018 Section 4.5.6 and 4.5.7 in buildings with flat slabs systems, beam-and-slab systems with A2 and A3 irregularities or transition floors. And it is necessary to ensure that the slab has sufficient thickness to resist in-plane effects. Especially in systems with slab discontinuities, the number of considered masses will need to be increased to simulate the irregularity adequately because a single rigid diaphragm will not be sufficient to reflect the situation. A flexible diaphragm can be used

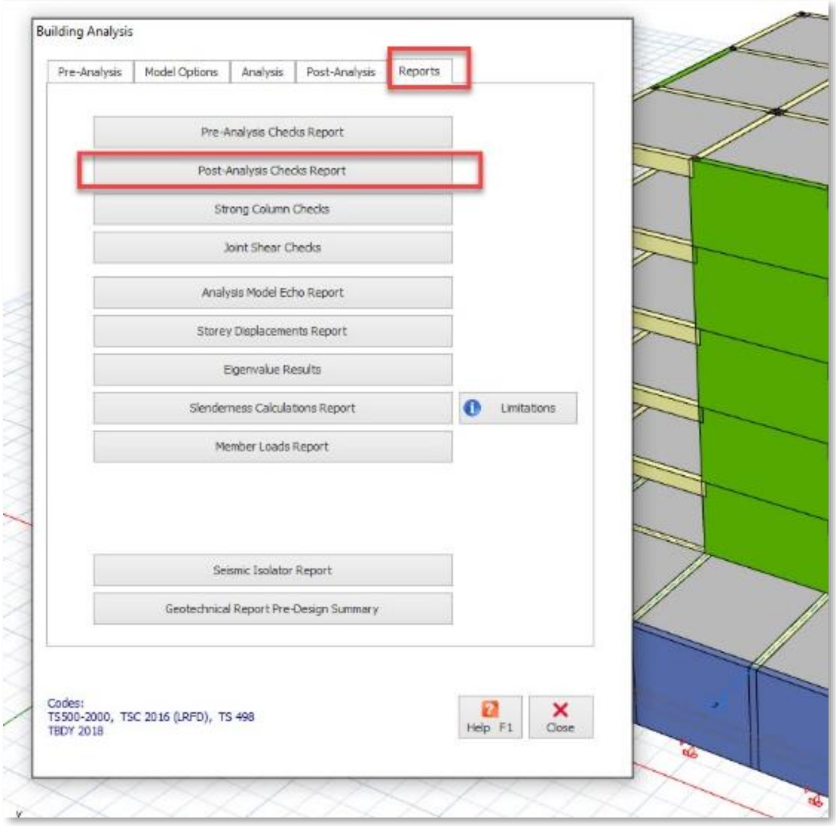
by turning off the rigid diaphragm for the particular storey and meshing the floor to make this possible in ProtaStructure. In the **'Finite Elements Mesh'** section, the **'Include Slabs in the Building Model'** option can be clicked, and the floors defined as flexible slabs must be unchecked in the **'Storeys to be Meshed'** section. In the **'Slab Stiffness Coefficients'** section, the **'In-Plane (Membrane)'** and **'Bending'** modifiers can be entered by engineering judgment. If these values are entered equal to 1, the flexible diaphragm is assumed using the slabs' gross (uncracked) in-plane and out-of-plane section properties. Values less than 1, will reduce the stiffness of the slabs.

- o In the **'Shell Element Size'** section, the shell size can be entered as a minimum of 50 cm and a maximum size of 50% more than the minimum size. A margin should always be left between the minimum and maximum size. ProtaStructure can also use dimensions smaller than the entered minimum value where required.

- The analysis is completed after all pre-analysis checks are done. By clicking on the **'Post-Analysis Checks Report'**, the results can be accessed under the heading **'Slab/Wall In-Plane Shear Stress Checks'** for TBDY2018 Section 7.11.5 and **'Slab In-Plane Stress Checks'** for Section 7.11.3.



Specifying the Slab Model



Post Analysis Checks Report

SLAB/WALL IN-PLANE SHEAR STRESS CHECKS:

(TBEC 2018 - Cl. 7.11.5)

ΔV_{Max} : Shear difference of upper and lower walls (Max. of all combinations)
L_{Dsm} : Total Length of slabs connected to the wall
A_{Dsm} : Total Section Area of slabs connected to the wall
τ_d : $\Delta V_{Max} / A_{Slab}$
τ_r : μρ f_{yd}
τ_{Limit} : 0.65 $(f_{ck})^{1/2}$ (τ_d Limiting value)
ρ_{sb} : Slab Connection Steel Percentage (for 1m)
A_{sb} : Slab Connection Steel Area (added to bending steel)
P : Axial load to be supported by each transfer beam
A_{sg} : Required web reinforcement of beam under tension
σ_b : Stress developed in beam under compression
σ_{Limit} : 0.5 f_{ck} (value that does not necessitate confinement reinforcement σ_b)

Wall	ΔV_{Max} (kN)	L_{Slab} (m)	A_{Slab} (m²)	τ_d (kN/m²)	ρ_b	A_{sb} (cm²/m)	Transfer Beams	P (kN)	A_{sg} (cm²)	σ_b (kN/m²)
Storey: 1										
P6	655.45	10.000	1.50	436.96 ≤3560.2 ✓	0.120	1.79				
P18	657.35	10.000	1.50	438.23 ≤3560.2 ✓	0.120	1.80				
P19	657.29	10.000	1.50	438.19 ≤3560.2 ✓	0.120	1.80				
P7	655.51	10.000	1.50	437.01 ≤3560.2 ✓	0.120	1.79				
P8	385.37	5.000	0.75	513.83 ≤3560.2 ✓	0.141	2.11				
P9	414.31	5.000	0.75	552.41 ≤3560.2 ✓	0.151	2.27				
P10	371.63	5.000	0.75	495.51 ≤3560.2 ✓	0.136	2.04				
P11	401.24	5.000	0.75	534.99 ≤3560.2 ✓	0.146	2.20				
P12	378.52	5.000	0.75	504.69 ≤3560.2 ✓	0.138	2.07				
P24	378.81	5.000	0.75	505.09 ≤3560.2 ✓	0.138	2.07				
P23	401.71	5.000	0.75	535.61 ≤3560.2 ✓	0.147	2.20				
P22	372.69	5.000	0.75	496.92 ≤3560.2 ✓	0.136	2.04				
P21	417.10	5.000	0.75	556.13 ≤3560.2 ✓	0.152	2.28				
P20	387.76	5.000	0.75	517.02 ≤3560.2 ✓	0.142	2.12				
P17	386.59	5.000	0.75	515.45 ≤3560.2 ✓	0.141	2.12				
P16	415.61	5.000	0.75	554.14 ≤3560.2 ✓	0.152	2.28				
P15	372.73	5.000	0.75	496.97 ≤3560.2 ✓	0.136	2.04				

Slab/Wall In-plane Shear Stress Checks

SLAB IN-PLANE STRESS CHECKS:

(TBEC 2018 - Cl. 7.11.3)

σ_c : Average Axial Compressive Stress
σ_{cLimit} : 0.85 f_{cd} (σ_c Limit Value)
σ_t : Average Axial Tensile Stress
σ_{tLimit} : f_{ctd} (σ_t Limit Value requiring Tensile Reinforcement)
τ_d : Average Shear Stress
τ_r : 0.65 f_{ctd} + ρ f_{yd}
τ_{Limit} : 0.65 $(f_{ck})^{1/2}$ (τ_d Limit Value)
A_{st} : Additional tension reinforcement area (for 1m)
A_{sv} : Additional shear reinforcement area (for 1m)

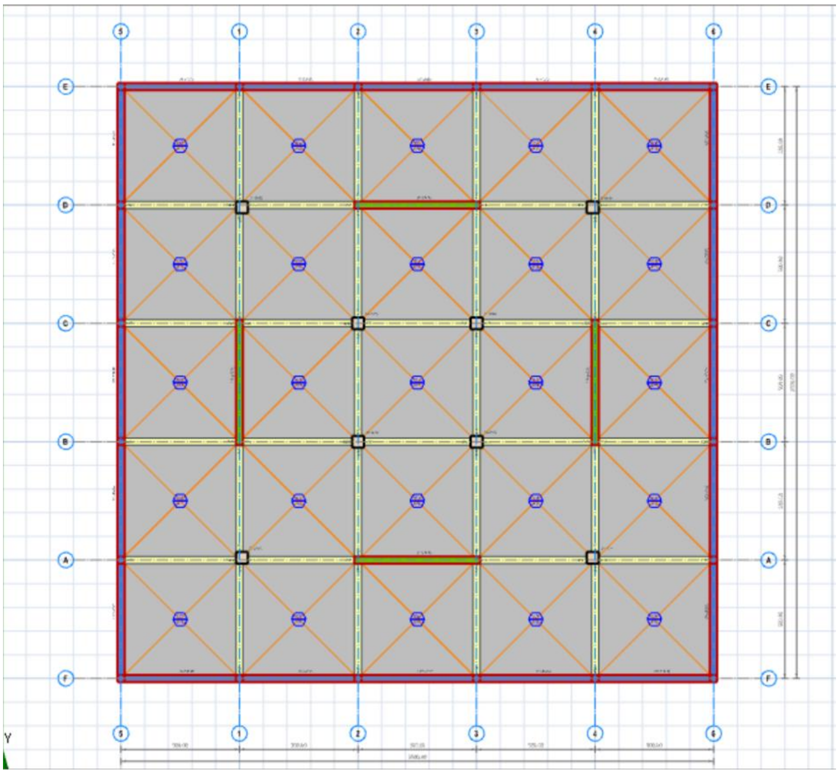
All stresses in the table are multiplied with overstrength factor (D).

Slab	σ_c (kN/m²)	σ_t (kN/m²)	τ_d (kN/m²)	A_{st} (cm²/m)	A_{sv} (cm²/m)
Storey: 1					
D109	607.00 ≤ 17000 ✓	0.00≤ 1280 ✓	371.08 ≤ 3560.2 ✓	-	-
D107	620.58 ≤ 17000 ✓	0.00≤ 1280 ✓	368.32 ≤ 3560.2 ✓	-	-
D108	519.23 ≤ 17000 ✓	0.00≤ 1280 ✓	374.70 ≤ 3560.2 ✓	-	-
D118	547.42 ≤ 17000 ✓	0.00≤ 1280 ✓	373.82 ≤ 3560.2 ✓	-	-
D114	532.19 ≤ 17000 ✓	0.00≤ 1280 ✓	370.44 ≤ 3560.2 ✓	-	-
D119	608.82 ≤ 17000 ✓	0.00≤ 1280 ✓	369.14 ≤ 3560.2 ✓	-	-
D117	581.48 ≤ 17000 ✓	0.00≤ 1280 ✓	360.04 ≤ 3560.2 ✓	-	-
D113	636.51 ≤ 17000 ✓	0.00≤ 1280 ✓	318.18 ≤ 3560.2 ✓	-	-
D112	475.20 ≤ 17000 ✓	0.00≤ 1280 ✓	364.73 ≤ 3560.2 ✓	-	-
D101	256.32 ≤ 17000 ✓	0.00≤ 1280 ✓	325.02 ≤ 3560.2 ✓	-	-
D102	572.83 ≤ 17000 ✓	0.00≤ 1280 ✓	368.36 ≤ 3560.2 ✓	-	-

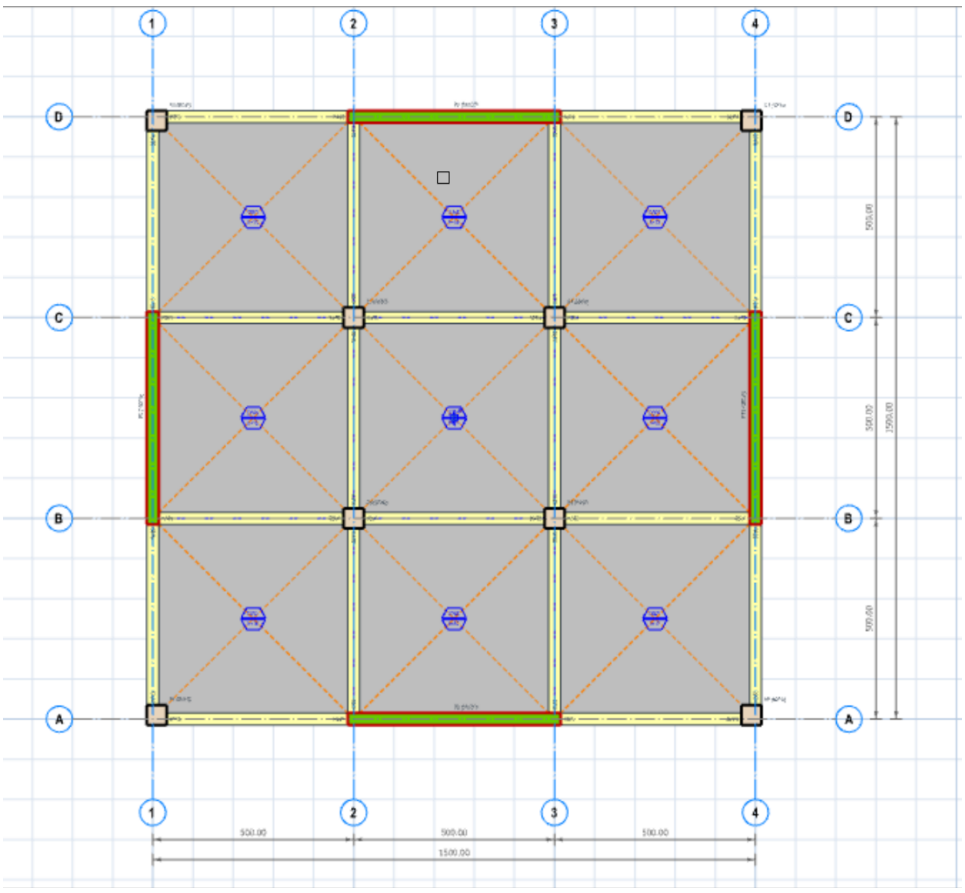
Slab In-plane Stress Checks

Explanation of the Post-Analysis Checks Report on the Sample Model

- The sample model consists of 1 basement with 5x5m spans and five storeys with 3x5m spans in the X and Y directions. This beam-slab model has 30x500 cm shearwalls on the exterior facades in X and Y directions, 50x50 cm columns, and 30x60 cm beams with 15 cm slab thickness. C30 and S420 concrete and steel reinforcement classes are chosen, respectively.

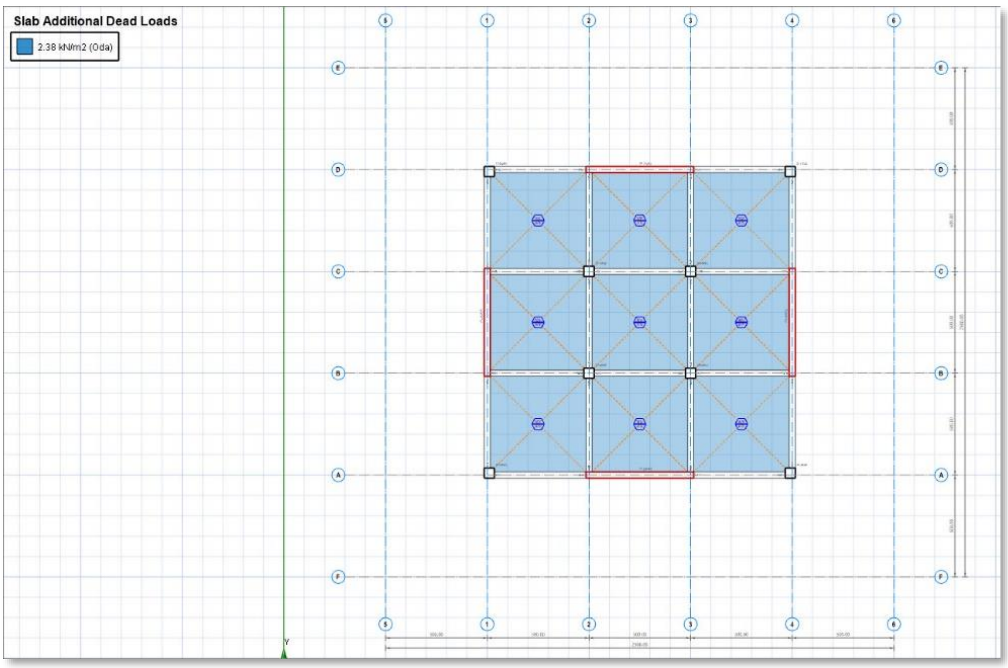


Sample Model Basement Floor Plan

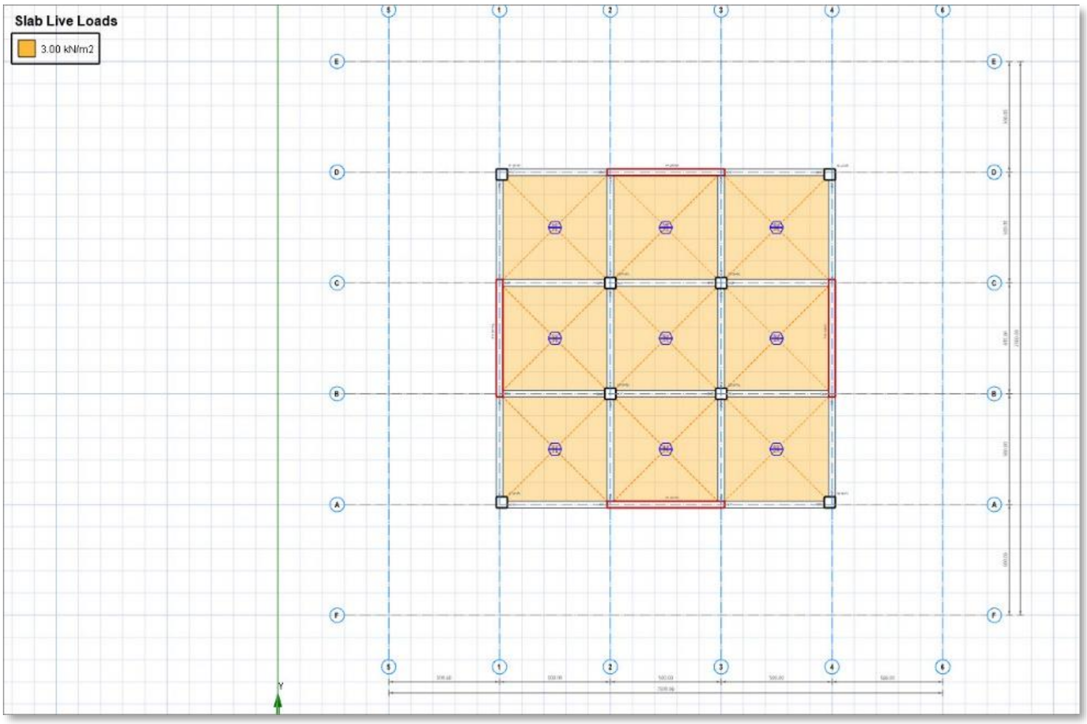


Sample Model Normal Floor Plan

- The dead and live loads considered in the example model are a self-weight of 3.75 kN/m^2 (for 15 cm slab thickness), an additional dead load of 2.38 kN/m^2, and a live load of 3 kN/m^2.

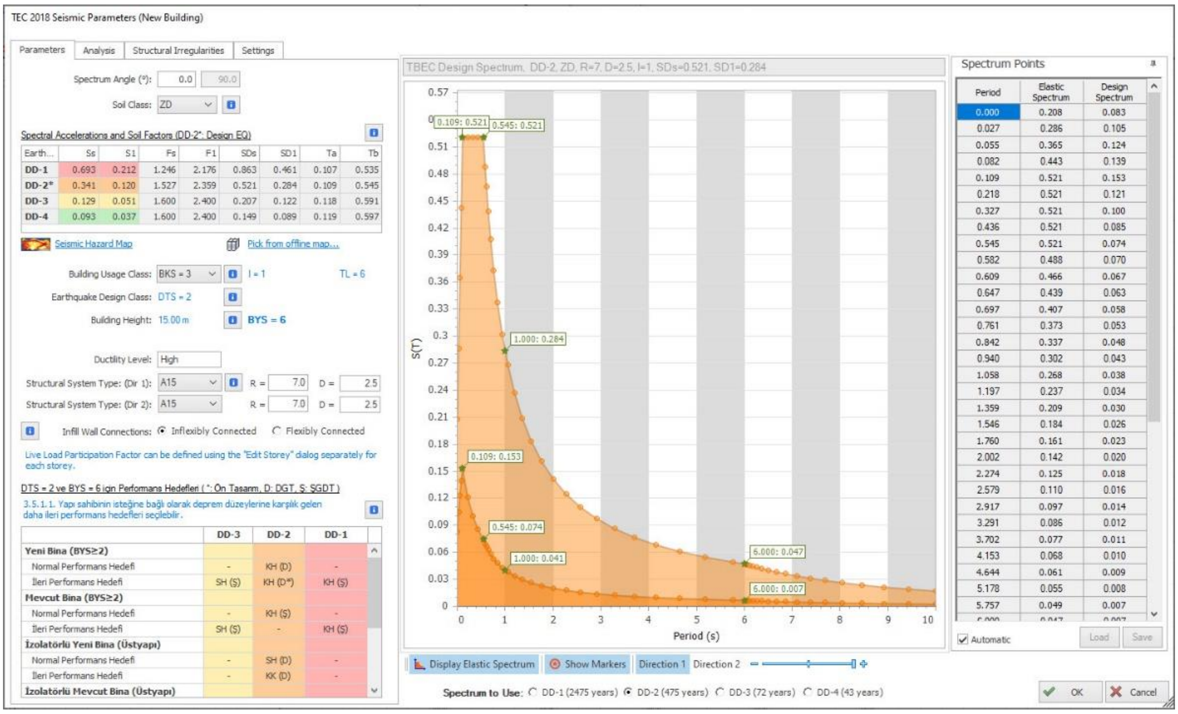


Sample Model Additional Dead Loads



Sample Model Live Loads

- For the seismic load, the point at 39.91394525° latitude and 32.84876888° longitude was selected offline from the Seismic Parameters Library. By choosing Modal Response Spectrum as the analysis type, the number of modes to be considered is 18. The seismic parameters used can be seen in the image below.



Sample Model Seismic Parameters

- The load combinations used in the analysis can be seen in the image below.

No	Combination	LL Red	R/C	Steel	G	Gc	Q	Qc	Qs1	Qs2	Ez	Ex+	ExB+	Ex-	ExB-	Ey+	EyB+	Ey-	EyB-
1	G+Q	☑	☑	☑	1.40	0	1.60	0	0	0	0	0	0	0	0	0	0	0	0
2	G+Qs1	☑	☑	☑	1.40	0	0	0	1.60	0	0	0	0	0	0	0	0	0	0
3	G+Qs2	☑	☑	☑	1.40	0	0	0	0	1.60	0	0	0	0	0	0	0	0	0
4	Gc+Qc+Ez+E...	☐	☑	☑	0	1.00	0	1.00	0	0	0.30	1.00	0	0	0	0	0	0.30	0
5	Gc+Qc+Ez-E...	☐	☑	☑	0	1.00	0	1.00	0	0	0.30	-1.00	0	0	0	0	0	-0.30	0
6	Gc+Qc+Ez+E...	☐	☑	☑	0	1.00	0	1.00	0	0	0.30	0	0	1.00	0	0.30	0	0	0
7	Gc+Qc+Ez-Ex-	☐	☑	☑	0	1.00	0	1.00	0	0	0.30	0	0	-1.00	0	-0.30	0	0	0
8	Gc+Qc+Ez+E...	☐	☑	☑	0	1.00	0	1.00	0	0	0.30	0	0	0.30	0	1.00	0	0	0
9	Gc+Qc+Ez-E...	☐	☑	☑	0	1.00	0	1.00	0	0	0.30	0	0	-0.30	0	-1.00	0	0	0
10	Gc+Qc+Ez+E...	☐	☑	☑	0	1.00	0	1.00	0	0	0.30	0.30	0	0	0	0	0	1.00	0
11	Gc+Qc+Ez-Ey-	☐	☑	☑	0	1.00	0	1.00	0	0	0.30	-0.30	0	0	0	0	0	-1.00	0
12	Gc+Ez+Ex+	☐	☑	☑	0	0.90	0	0	0	0	-0.30	1.00	0	0	0	0	0	0.30	0
13	Gc+Ez-Ex+	☐	☑	☑	0	0.90	0	0	0	0	-0.30	-1.00	0	0	0	0	0	-0.30	0
14	Gc+Ez+Ex-	☐	☑	☑	0	0.90	0	0	0	0	-0.30	0	0	1.00	0	0.30	0	0	0
15	Gc+Ez-Ex-	☐	☑	☑	0	0.90	0	0	0	0	-0.30	0	0	-1.00	0	-0.30	0	0	0
16	Gc+Ez+Ey+	☐	☑	☑	0	0.90	0	0	0	0	-0.30	0	0	0.30	0	1.00	0	0	0

Sample Model Load Combinations Table

Slab In-Plane Stress Checks (TBDY2018 Section 7.11.3)

It is assumed that the slabs behave semi-rigidly (flexible) when performing the 'Slab In-Plane Stress Check'. For this reason, these slabs should be modeled as a 'Finite Elements Mesh,' and the rigid diaphragm constraint must be turned off for the particular storey. The 'Overstrength Factor' D will be applied to the in-plane average tensile, compressive, and shear stresses due to seismic loads.

- After the analysis is completed, the results of the 'Slabs In-Plane Stress Checks' TBDY2018 Section 7.11.3 in the 'Post-Analysis Checks Report' can be seen in the image below.

SLAB IN-PLANE STRESS CHECKS:

(TBEC 2018 - Cl. 7.11.3)

σ_c : Average Axial Compressive Stress
$\sigma_{c\,Limit}$: 0.85 f_{cd} (σ_c Limit Value)
σ_t : Average Axial Tensile Stress
$\sigma_{t\,Limit}$: f_{ctd} (σ_t Limit Value requiring Tensile Reinforcement)
τ_d : Average Shear Stress
τ_r : 0.65 f_{ctd} + ρ f_{yd}
τ_{Limit} : 0.65 $(f_{ck})^{1/2}$ (τ_d Limit Value)
A_{st} : Additional tension reinforcement area (for 1m)
A_{sv} : Additional shear reinforcement area (for 1m)

All stresses in the table are multiplied with overstrength factor (D).

Slab	σ_c (kN/m²)	σ_t (kN/m²)	τ_d (kN/m²)	A_{st} (cm²/m)	A_{sv} (cm²/m)
Storey: 1					
D109	607.00 ≤ 17000 √	0.00 ≤ 1280 √	371.08 ≤ 3560.2 √	-	-
D107	620.58 ≤ 17000 √	0.00 ≤ 1280 √	368.32 ≤ 3560.2 √	-	-
D108	519.23 ≤ 17000 √	0.00 ≤ 1280 √	374.70 ≤ 3560.2 √	-	-
D118	547.42 ≤ 17000 √	0.00 ≤ 1280 √	373.82 ≤ 3560.2 √	-	-
D114	532.19 ≤ 17000 √	0.00 ≤ 1280 √	370.44 ≤ 3560.2 √	-	-
D119	608.82 ≤ 17000 √	0.00 ≤ 1280 √	369.14 ≤ 3560.2 √	-	-
D117	581.48 ≤ 17000 √	0.00 ≤ 1280 √	360.04 ≤ 3560.2 √	-	-
D113	636.51 ≤ 17000 √	0.00 ≤ 1280 √	318.18 ≤ 3560.2 √	-	-
D112	475.20 ≤ 17000 √	0.00 ≤ 1280 √	364.73 ≤ 3560.2 √	-	-
D101	256.32 ≤ 17000 √	0.00 ≤ 1280 √	325.02 ≤ 3560.2 √	-	-
D102	572.83 ≤ 17000 √	0.00 ≤ 1280 √	368.36 ≤ 3560.2 √	-	-

Slab In-plane Stress Checks

Compressive Stress Checks

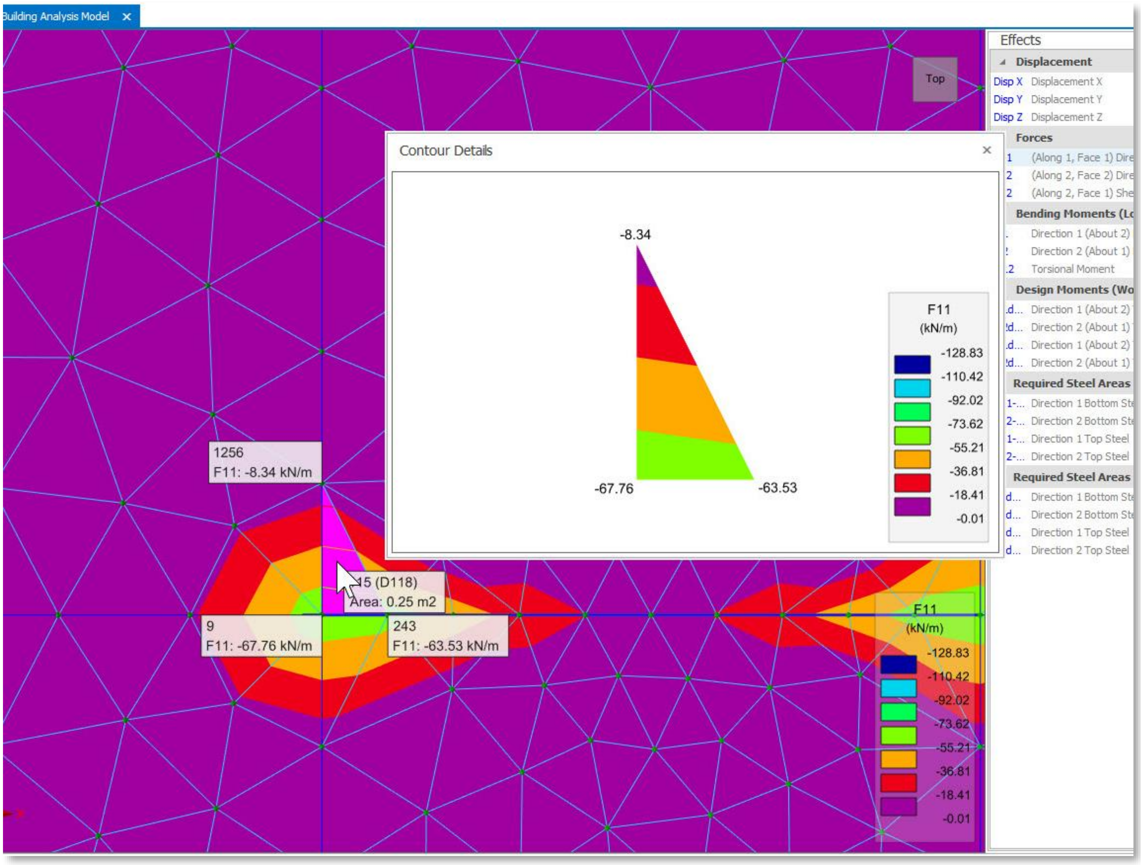
According to TBDY2018 Section 7.11.3, the average compressive stress should not exceed **0.85f_{cd}**.

In ProtaStructure, slab analysis is performed with the finite element method. Each slab is divided into triangular shell elements, and the average stresses are calculated from the maximum stresses occurring at the **I, J,** and **K** points of each triangle element. This process is done for all finite triangular elements in the slab. The total value is divided by the total number of triangular elements to obtain the average stress value. This calculation is made for all seismic load cases, and the most critical value is used. The maximum value is found by multiplying by the coefficient D.

$$\sigma_{AVERAGE\ COMPRESSION\ STRESS-SHELL} = D.\frac{\sum_{I,J,K} F}{3.\,h_{SHELL}} \quad (F > 0\ for\ compression)$$

$$\sigma_{AVERAGE\ COMPRESSION\ STRESS-SLAB} = \frac{\sum_{i=1}^{n} \sigma_{AVERAGE\ COMPRESSION\ STRESS-SHELL}}{n}$$

The average axial compression stress should not exceed **0.85f_{cd}**. The f_{cd} value is 20 MPa for concrete class C30.



Sample Model Triangular Shell Member

Tensile Stress Checks

According to TBDY2018 Section 7.11.3, when the f_{ctd} value is exceeded, the concrete cracks under the tensile stresses, and this tensile force must be satisfied by the slab reinforcement. If the axial tensile force is greater than f_{ctd}, the in-plane tensile stress shall not exceed $\rho.f_{yd}$, ρ being the ratio of reinforcement required for the flexural strength of the slab. If the tensile stress exceeds $\rho.f_{yd}$, required reinforcement must be provided in addition to the rebars calculated for gravity design.

In ProtaStructure, slab analysis is performed with the finite element method. Each slab is divided into triangular shell elements, and the average stresses are calculated from the maximum stresses occurring at the **I, J,** and **K** points of each triangle element. This process is done for all finite triangular elements in the slab. The total value is divided by the total number of triangular elements to obtain the average stress value. This calculation is made for all seismic load cases, and the most critical value is used. The maximum value is found by multiplying by the coefficient D.

$$\sigma_{AVERAGE\ TENSION\ STRESS-SHELL} = D.\frac{\sum_{I,J,K} F}{3.h_{SHELL}} \quad (F < 0\ for\ tension)$$

$$\sigma_{AVERAGE\ TENSION\ STRESS-SLAB} = \frac{\sum_{i=1}^{n} \sigma_{AVERAGE\ TENSION\ STRESS-SHELL}}{n}$$

If the axial tensile stress exceeds the $0.85f_{cd}$ value, the value of $\rho.f_{yd}$ should not be exceeded. f_{ctd} value is 1.28 MPa for concrete class C30. f_{yd} value is 365 MPa for S420 reinforcing steel.

In-Plane Shear Stress Checks

In ProtaStructure, slab analysis is performed with the finite element method. Each slab is divided into triangular shell elements, and the average stresses are calculated from the maximum stresses occurring at the **I, J,** and **K** points of each triangle element. This process is done for all finite triangular elements in the slab. The total value is divided by the total number of triangular elements to obtain the average stress value. This calculation is made for all seismic load cases, and the most critical value is used. The maximum value is found by multiplying by the coefficient D.

$$\tau_{AVERAGE\ SHEAR\ STRESS-SHELL} = D.\frac{\sum_{I,J,K} F_{12}}{3.h_{SHELL}}$$

$$\tau_{AVERAGE\ SHEAR\ STRESS-SLAB} = \frac{\sum_{i=1}^{n} \tau_{AVERAGE\ SHEAR\ STRESS-SHELL}}{n}$$

According to TBDY2018 Section 7.11.3, the horizontal shear stresses within the floor plane should not exceed the value calculated by the formula below.

$$\tau < \tau_r = 0.65 f_{ctd} + \rho f_{yd}$$

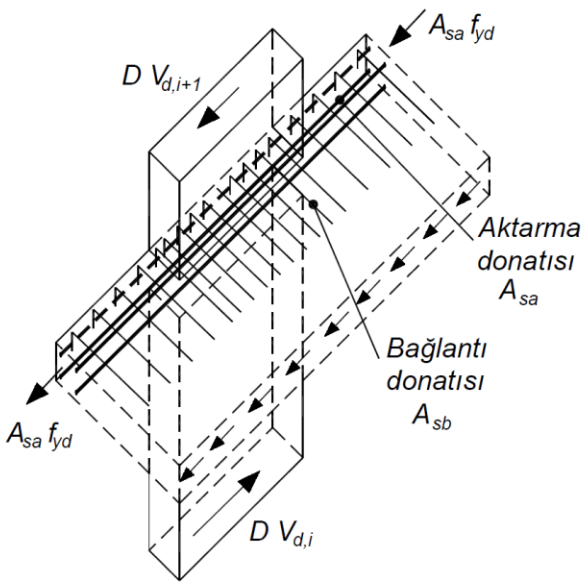
The ρ value used in the limit value is the ratio of the slab reinforcement to be placed in the direction parallel to the shear stress and remaining from the reinforcement required for the flexural strength. Horizontal shear stresses must also satisfy the following condition.

$$\tau < 0.65\sqrt{f_{ck}}$$

f_{ctd} value is 1.28 MPa for concrete class C30. f_{yd} value is 365MPa for S420 reinforcing steel.

Slab/Wall In-Plane Shear Stress Checks (TSC2018 Section 7.11.5)

In flat slab or beam-slab systems, it is necessary to prove that the earthquake loads are safely transferred from the slabs to the vertical structural members. This check is required primarily for buildings with A2 and A3 irregularities, discontinuities, and gaps. The earthquake forces transferred from the slab to the shearwall in the wall's major direction can be calculated as the difference of shear forces between the lower and upper floors. The shear forces are increased with the **'Overstrength Factor' D** of earthquake effects. The shear friction on the wall-slab joint must resist the unbalanced shear force. If it is not sufficient alone, additional shear friction reinforcement, A_{sb}, and transfer reinforcement, A_{sa} must be provided, as shown in the figure.



Slab-Shearwall Overlapping Surface

Horizontal Shear Stress Checks

According to TBDY2018 Section 7.11.5, the difference of the wall shear forces DV_d shall not exceed the sum of the horizontal shear forces $2A_{SA}f_{yd} + \mu A_{sb}f_{yd}$. The A_{sa} used at the limit value is defined as the transfer reinforcement. A_{sa} is the transfer reinforcement at the slab-wall joint. Due to the earthquake force, the maximum shear on the shearwalls will be on the ground floor shear walls.

$$D_{Vd} = D_{Vd,i} - D_{Vd,i+1} =< 2A_{sa}f_{yd} + \mu A_{sb}f_{yd}$$

f_{yd} value is 365MPa for S420 reinforcing steel. It is given as μ ≤ 1 in TSC2018 Section 7.11.5.

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