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Phenomenological Aspects of RC Slab Behavior against Horizontal and Vertical Loadings

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Abstract

Reinforced concrete system is the most widely applied structural system in Turkey, where slabs are considered the primary structural member which play an essential role in diaphragm actions. The concrete slab type directly affects the height of the building, the ductility level, the design calculations, and the cost of construction. In earthquake prone countries (i.e. Turkey), the type of slab affects the ductility levels of structure hence, it affects the base shear force and the cost as well. It is worth pointing out that the new 2018 Building Earthquake Code of Turkey provides more precise provisions concerning the selection of slab systems which is no more limited to the technical calculations only. One important update of the new national regulations is that for flat slab reinforced concrete buildings, the implementation of shear wall structural members becomes a mandatory. This work provides a detailed interpretation of the new national regulations concerning the selection of slab type, the work also briefly discusses different types of reinforced concrete slabs and the parameters which influence the selection process of the slab type.

1. Introduction

It is well known that cement paste plays a primary role within the concrete mixture and influences most important features of the mix by binding the aggregate to develop the workability, compressive strength, and durability as well. In the same context, a slab presents a primary part of the structural system in reinforced concrete buildings. The concrete slabs also compile the structural system as a whole by connecting the columns/walls and beams to each other.

Slabs are classified according to different criteria and sometimes-different names are used for the same type of slab. This work discusses three type of slabs as slabs on beams, flat slabs and ribbed slabs. The parameters that generally affect the selection of the slab type are [1]:

(1) The cost of slab

(2) Maximum span length

(3) Seismicity of the region

(4) The severity and type of the imposed loads,

(5) The purpose of the use of the building,

(6) The compliance with usage changes,

(7) Plan geometry of the building,

(8) Sensitivity of the goods and devices to be carried,

(9), Knowledge and skills of technical staff,

(10) Presence of console slabs

Figure 1 shows the internal forces (stresses) which occur in the slab under the imposed horizontal and vertical loads. According to the direction of imposed loads, two normal stresses and two shear stresses occur, refer to Figure 1.

The punching failure, which is commonly known in flat slabs, occurs when the in-plane shear stress exceeds the punching strength. Flexural cracks occur when the tensile stress, which is perpendicular to the plane of the slab, exceeds the tensile strength.

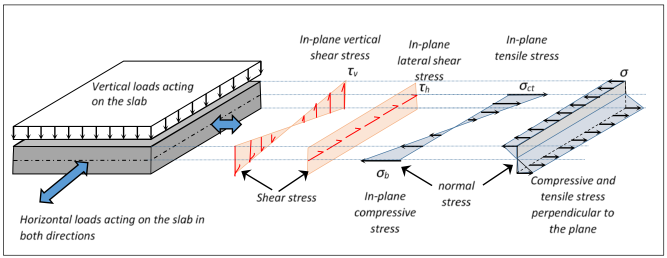


Figure 1. The internal forces in a slab due to the imposed vertical and horizontal loads [1, 2].

The most common damage under vertical loads is deflection. Figure 2 shows a slab damaged by deflection due to the applied vertical loads. The punching failure is another fatal damage which may occur under vertical loads, refer to Figure 3.

Figure 2. A cracked slab due to excessive deflection under vertical loads

Figure 3. Punching damage under vertical loads

For countries that are located in high seismic regions such as Turkey, the seismicity of the region significantly governs the selection of slab systems, the following paragraphs explain the reasons and consequences related to this issue in detail.

2. Selection of slab system for design purposes

The role of the slab system differs according to the characteristics of the impact loadings acting on the building in question. In the case of static vertical loads including dead and live loads, slabs are designed to transfer the imposed static vertical loads to the supporting beams or directly to the columns/shear walls if there are no beams.

In the case of lateral loads such as earthquakes and wind, slabs are responsible for distributing the lateral loads to the vertical bearing elements such as columns and shear walls consistent with their stiffness.

When a structure is exposed to external impact which can result in a support collapse for example, slabs along with the beams provide the adaptation of the structural system, and ensure that all elements resist the external impact together. With no beams, only slabs perform the task of ensuring adaptation between the vertical structural elements.

If slabs do not have sufficient strength and/or rigidity to resist the loads acting upon them, severe damages will occur at various levels based on the intensity of the imposed loads and the properties of the structural system.

Reinforced concrete slabs; as stated earlier; are classified into three main categories as follows: (1) slabs on beams, (2) flat slabs, and (3) ribbed slabs. Naturally, each group has advantages and disadvantages according to their behavior under various loads.

Literature studies have thoroughly discussed the behaviour of slabs under vertical static loads. However, in countries which are located in active earthquake regions such as Turkey, where devastating earthquakes occur, it has been revealed that slabs also have very important role during earthquakes.

Slabs significantly affect the earthquake design of a building through three parameters, **A-Ductılıty Level, B-Buıldıng Heıght,** and **C-Overstrength Factor**. The aforementioned parameters affect each other as well.

A-Ductılıty Level:

The ductility level is one of the most important parameters to determine the earthquake loads that will affect the structure. The selected ductility level may even cause the earthquake load to be twice as large. According to TBDY-2018, the following four parameters affect the selection of the ductility level:

1. Seismicity of the region where the building is located (DTS: Earthquake Design Class),

2. Building height (BYS: Building Height Class),

3. Type of slab system

4. The features of structural system (whether there are shear walls and how much lateral loads are imposed upon them)

Figure 4 presents a flow diagram for the effects of the aforementioned parameters. It can concluded that slabs on beams are the most appropriate type for a system with high ductility level, and the ribbed slabs, as well as the hollow slabs, do not fit well with this level of high ductility. The slabs on beams fall between these two types of slab.

DTS: Earthquake Design Class

A11: Buildings in which all earthquake loads are fully resisted by reinforced concrete frames with high ductility level

A12: Buildings in which all earthquake loads are fully resisted by reinforced concrete coupled structural walls with high ductility level

A13: Buildings in which all earthquake loads are fully resisted by reinforced concrete shear walls without openings and with high ductility level

A21: Buildings in which all earthquake loads are resisted by reinforced concrete frames with limited ductility level and coupled structural walls with high ductility level

A31: Buildings in which all earthquake loads are fully resisted by reinforced concrete frames with limited ductility level.

A32: Buildings in which all earthquake loads are fully resisted by reinforced concrete structural walls with no openings with limited ductility level

B31: Buildings in which seismic loads are fully resisted by prefabricated frames of limited ductility level with connections capable of cyclic moment transfer

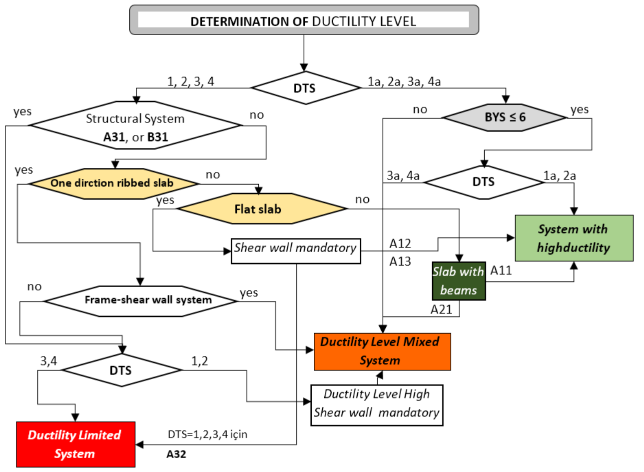


Figure 4. Determination of ductility level for structural systems [1, 2].

B-Buıldıng Heıght:

Until 2019, there was no unified limitation on the height of buildings overall Turkey, the applied limitations were based on the individual local governments. Since there were no limitations on the height of the building in the earthquake regulation, anyone can build a structure at any height. However, according to the new Turkish Earthquake Regulations 2018 [3], it has become impossible to construct a building with a random desired height. The following parameters limit the height of the building:

1) Earthquake Design Class (1, 1a, 2, 2a, 3, 3a, 4, 4a)

2) Structural System Features

a) Slab system (slab on beams, flat slab or one direction ribbed slab)

b) Ductility Level (limited, mixed or high)

c) Whether there is a shear wall (solid or coupled)

Given this, the most effective parameter is the slab system. According to the national earthquake regulation 2018, the type of flooring system plays a main role in determining the height of the building. The following diagrams show the effect of slab type on the height of the building, refer to Figure 5, Figure 6, and Figure 7 for ribbed slabs, flat slabs, and slabs on beams respectively.

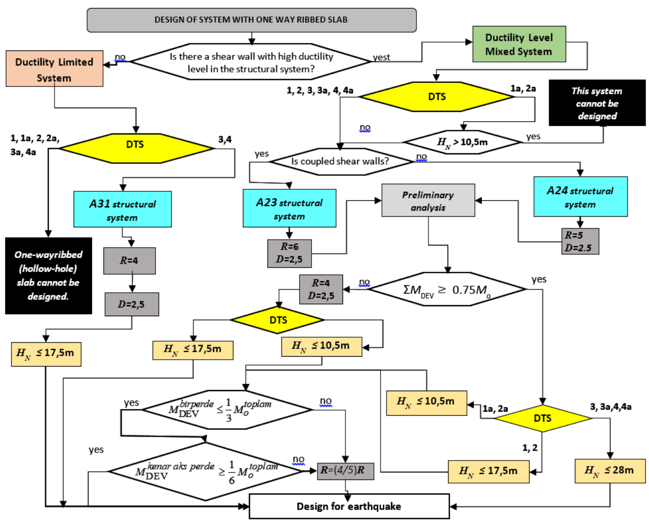


Figure 5. Structural systems and slab design that can be applied according to the ductility level in one direction ribbed slab [1, 2].

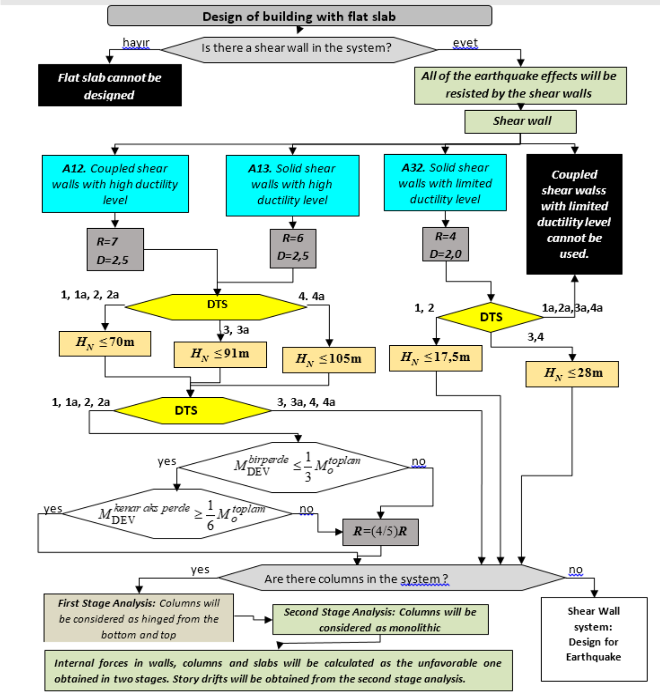
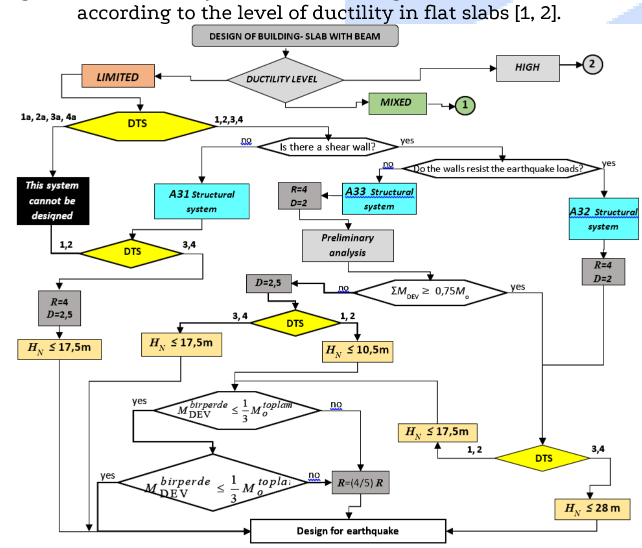


Figure 6. Structural system and slab design that can be considered according to the level of ductility in flat slabs [1, 2].



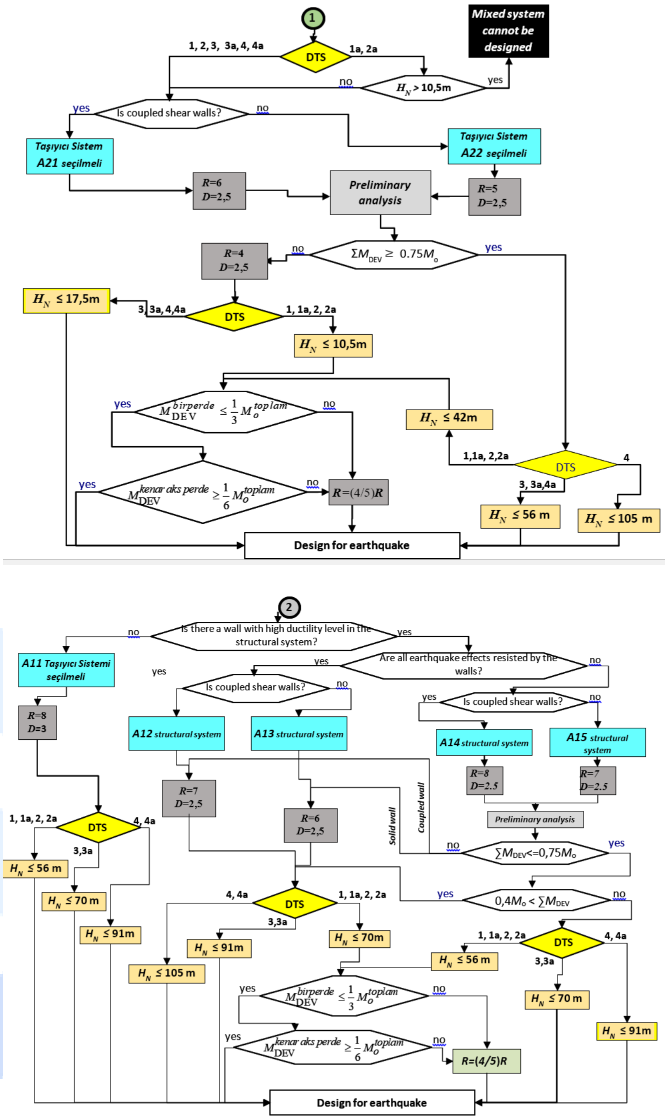


Figure 7. Structural systems and slab design that can be considered according to the level of ductility in slabs on beams [1, 2].

C- Over-strength Factor

The over-strength factor is included in the design processes according to the slab type. The issues related to over-strength factor are mentioned in the following two paragraphs concerning the design of slabs on beams and flat slabs.

Over-strength factor D is applied to the average in-plane tensile, compressive, and shear stresses that occur under earthquake loads in buildings with slabs on beams and flat slab.

The earthquake load which is transferred from the slab to the wall or the wall arm in the strong direction is obtained as the difference of the wall shear forces (DVd), which considers the over strength factor at the lower and upper sections of the floor level of buildings with flat slab or slab on beams, where it is necessary to show that the earthquake loads are safely transferred from the slabs to the vertical load-bearing elements.

3. Conclusions

Similar to the task of cement paste, which connects aggregates to each other; slabs in reinforced concrete structural systems connect the vertical structural elements together such as columns and shear walls, and ensure that the system responds as a whole. In the case of slabs on beams, the slabs perform this important task together with the beams. In contrast, with no beams, flat slab performs this important task on its own. In the case of ribbed slabs, the task is carried out by the slab and beams which are called pillow beams.

The behavior of slabs under vertical loads is different from the behavior under horizontal loads. It transfers the vertical loads acting on it to the supporting beams or directly to the vertical structural elements. For this transfer task, its bending and shear/punching capacities in the direction perpendicular to its plane are effective. However, the scope of the task expands further if the building is subjected to lateral loads. Where the slabs are designed to resist the vertical loads acting on it with out-of-plane capacities in general, and to resist the in-plane stresses caused by the horizontal loads. Given this, it is extremely important for a slab to act as a rigid diaphragm in order to fulfill its duty. Otherwise, the slabs will be damaged because they cannot fulfill the task of transferring the lateral loads to the vertical structural elements in proportion to their rigidity.

Earthquake loads demand much more complicated behavior of slabs. The structure resists the inertial forces that occur due to the mass distribution. The structure responds according to the rigidity of its vertical structural members. In addition to the in-plane axial forces, the in-plane shear stresses caused by the torsional moment occur in the slab as well. Therefore, considering the earthquake loads, the slab has to resist all the effects that may be distributed unevenly both in the out of plane direction as well as the in-plane direction. In each revision, the earthquake regulations enhance the calculations and designs of slabs more and more. TBDY-2018, which was applied in 2019, provides very important innovations in terms of both slab modeling and earthquake calculations and designs, as detailed in the text.

Declaration of Conflict of Interests

The author declare that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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3. Testing process

2.1. Test specimens and properties

In this research, 14 laboratory specimens in two groups with verified dent numbers (d2, d4, and d6) and with dents at different depths of t and 2t are examined. The first group of specimens (seven specimens), labelled 'without CFRP', and the second group, 'with CFRP', were loaded under hydrostatic pressure. Each group contained a perfect model and a perfect model with an entire surface of CFRP, with the remaining specimens having a dent with amplitudes of t and 2t (t = thickness of the cylindrical shell). A perfect model and a perfect model with entire-surface CFRP were used for control in each group. The details of the CFRP and epoxy are presented in Table 1, and the details of the specimens are presented in Table 2 and Fig. 1. The CFRP strip was calculated with the formula $3b_d \times (L_d + 2b_d)$, where $3b_d$ is the width of the CFRP strip, and $L_d + 2b_d$ is the length of the CFRP strip (L_d = dent length, and b_d = dent width).

Table 1. Tensile Properties of CFRP and epoxy used

Name and Supplier	Type	ρ (g/cm^3)	E (GPa)	σ (MPa)	ε (%)
BASF, MasterBrace, 300/50 CBS	Thermoplastic	1.77	227	3800	1.67
BASF, MasterBrace, SAT 4500	Low viscosity epoxy	0.983	3.034	55.2	3.5

Table 2. Initial geometries of test models

Group	Specimen	Model	L_d	h_d	b_d	FD	d_i
Without CFRP	t-2t-d2	M1	$h_c/2$	t	2t	-	2
	2t-4t-d2	M2	$h_c/2$	2t	4t	-	2
	t-2t-d4	M3	$h_c/2$	t	2t	-	4
	2t-4t-d4	M4	$h_c/2$	2t	4t	-	4
	t-2t-d6	M5	$h_c/2$	t	2t	-	6
	2t-4t-d6	M6	$h_c/2$	2t	4t	-	6
	Perfect model	M7	-	-	-	-	-
With CFRP	CFRP-t-2t-d2	M8	$h_c/2$	t	2t	$3b_d \times (l_d + 2b_d)$	2
	CFRP-2t-4t-d2	M9	$h_c/2$	2t	4t	$3b_d \times (l_d + 2b_d)$	2
	CFRP-t-2t-d4	M10	$h_c/2$	t	2t	$3b_d \times (l_d + 2b_d)$	4
	CFRP-2t-4t-d4	M11	$h_c/2$	2t	4t	$3b_d \times (l_d + 2b_d)$	4
	CFRP-t-2t-d6	M12	$h_c/2$	t	2t	$3b_d \times (l_d + 2b_d)$	6
	CFRP-2t-4t-d6	M13	$h_c/2$	2t	4t	$3b_d \times (l_d + 2b_d)$	6
	Perfect model with entire-surface CFRP	M14	-	-	-	Entire-surface CFRP	-

Specimen: $h_d - b_d - d_i$; h_d: Dent depth; b_d: Dent width; d_i: dent number (d2, d4, and d6 as two, four, and six dents, respectively); L_d: Dent length; h_c: Height of cylinder (1250 mm for all models); t: Thickness of cylinder (t = 1 mm for all models); FD: Fibre dimensions (width × height); R: Radius (500 mm)

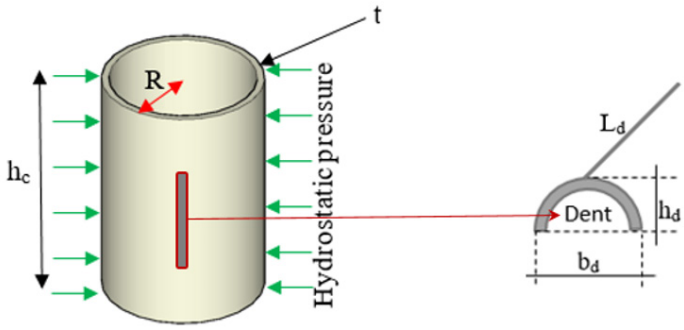

Figure 1. Details of test model

2.2. Testing system and manufactured specimen

The test machine consists of two plates: upper and bottom plates with dimensions of 1500 × 1500 mm and a plate thickness of 30 mm. The plates were first cut into 1500 × 1500-mm sizes by a CNC cutting device and then ring-cut with a CNC cutting machine. Soldering was applied to minimise the error rate and improve the weld performance via the seam fusing method [4–6, 20–22]. To decrease the initial distortion and residual stress, the edges of the cylinder were joined through soldering. The steel plates were cut in the exact dimensions of the models and rolled into cylinders by a rolling machine.

Fig. 2 shows the test machine used in this research. In one of the plates on the upper part, there are two holes in the middle of the passage of the vacuum hose from the first hole. The load cell is inserted into the second hole, and four sets of studs on the four sides of the plate lift the plate using a welding crane. On the sides of the plates, three holes of the bolt are intended to be six in total, until the configuration shown in Fig. 2 is achieved. The reason for these six bolts is the installation of a top plate assembly, which, when tested with the crane, prevents these bolts from entering the axial load into the cylinder.

After the test machine was manufactured, it was time to build laboratory samples. Three tensile coupon tests were performed to obtain the material properties. The average yield and failure stresses were found to be 198.8 MPa and 342.4 MPa, respectively. Young's modulus was calculated to be 210 MPa, and Poisson's ratio was obtained as 0.29. To make samples, sheets with a thickness of 1 mm were prepared. Ten sheets were cut to 1250 mm in height and 3140 mm in length with scissors. Then, a cylindrical roller was used to create rolled specimens. During the welding, it was considered that the lowest porosity and inadequacy of welding on the laboratory models were not achieved, and the models were prepared without imperfections in welding. In addition, during rolling, we were careful not to cause any imperfections.

The edges of the models were welded through metal inert gas welding by using 0.8-mm electrodes for a 1-mm weld thickness. After the creation of the laboratory models, it was necessary to create inadequacies. To create disadvantages in the models, stainless steel shapes (SPKR) were made in the form of cutting and the wire cut method. Fig. 2 shows the dent piece for the experimental tests. First, a dent length was indicated at the centre of the height of the model with a ruler and a marker, and then a four-base was laid inside the model.

A static load pump was employed with a maximum load of 900 kN, stroke of 300 mm, and constant speed of 0.016 mm/s. The pump was used to create dents in the models [23–30]. In Fig. 2, the dent implementation in the models is shown. All dents were manufactured to be inward and equidistant from each end for all of the models. Furthermore, the dents were manufactured with equal angles (360^0/dent number). For the group with CFRP models that were to be used, two-component epoxy-coated adhesive was stuck onto the specified parts. Table 2 lists the data for the experimental models.

To install the laboratory models, the following was accomplished. Beginning at the bottom of the laboratory model, after fitting the model on the bottom plate of the silicone silencer model, the edge of the model was filled to the plate inside and outside the cylinder to prevent air from escaping from the inside of the cylinder. After that, to fit the other side of the cylinder, the bolts around the device were opened, and the upper plate was slowly raised and guided by a crane to the cylinder. Prior to guiding the top plate, the bolts were adjusted to the height of the cylinder to prevent a sudden collision of the plate with the cylindrical model.

Finally, after inserting the top plate, the bolt shown in Fig. 2 was closed to prevent gravity loading on the cylindrical model. Alternately, the crane transported the top plate during the test to maintain a gravity-load-avoidance sample. After the plate around the cylinder was filled with silicon glue, silicon was added to an argon boil in order to prevent air from escaping.

After performing the above steps, four metal support rings, two on the bottom and two on the top of the cylinder, were installed so that all laboratory models with a simple support were closed only in the radial direction.

Nomenclature

X : The length of the specimen in horizontal direction
Y : The length of the specimen in vertical direction

Declaration of Conflict of Interests

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