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Increasing the Vertical Load Capacity of Reinforced Concrete Waffle Slabs With Varying Operating Loads Using CFRP

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Keywords: CFRP, reinforced concrete structures, retrofitting, waffle slabs, earthquake

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ABSTRACT

The subject of the study is to determine the earthquake performance according to TBEC2018 principles of the existing medicine production facility with a frame system, which was built with conventional RC method in Çorlu-Tekirdag and to evaluating the use of CFRPs (Carbon Fiber Reinforced Polymers) for increasing the vertical load capacity of waffle slabs. In a highly hygienic environment, retrofitting alternatives have been investigated and structural safety comparison has been made. In the earthquake retrofitting application of the building, the advantages of retrofit with composite materials were utilized and advantages and disadvantages were determined compared to traditional methods. The live load value of 750 kg/m2 was increased to 1000 kg/m2 with the change of use. After this change, CFRP strips and fabrics were used to increase the load bearing capacity of the slabs. In addition, the change in the mode shapes and storey drifts of the structure was checked after the live load increase. The effect of CFRP reinforcement technique applied to waffle slabs, beams and columns on the stiffness, ductility and displacements of the structure was evaluated. The safety of the structure has been established according to the TBEC2018 and the effect of CFRP on the axial compression, bending and shear resistance of the structural elements was determined according to 1000 kg/m2, which is the live load capacity required by Covid19 vaccine production.

İşletme Yükleri Değişen Betonarme Kaset Döşemelerin CFRP ile Düşey Yük Kapasitelerinin Arttırılması

ÖZ

Çalışmanın konusu, DBYBHY2007'ye göre tasarım ve analizleri tamamlanan, Çorlu-Tekirdağ'da konvansiyonel betonarme yöntemi ile inşaa edilmiş, çift yönlü dişli döşemelerin (kaset döşeme) kullanıldığı çerçeve sistemli mevcut ilaç üretim tesisinin, değişen işletme yükleri altında TBDY2018 yönetmeliği esaslarına göre deprem performansının belirlenmesi ve çift yönlü dişli döşemelerin düşey yük kapasitelerinin artışı için CFRP (karbon esaslı lifli polimerler)'lerin kullanımının uygunluğunun değerlendirilmesidir. İlaç tesisi gibi oldukça hijyenik bir ortamda güçlendirme alternatifleri araştırılmış ve yapısal güvenlik karşılaştırması yapılmıştır. Yapının deprem güçlendirme uygulamasında kompozit malzemelerle güçlendirmenin avantajlarından yararlanılmış ve geleneksel yöntemlere göre avantaj ve dezavantajları belirlenmiştir. 750 kg/m2 olan hareketli yük değeri kullanım değişimi ile 1000 kg/m2'ye yükseltilmiştir. Bu değişimin ardından CFRP lamine ve kumaşlar ile döşeme yük taşıma kapasitesi arttırılmıştır. Ayrıca yapının mod şekilleri ve göreli ötelemelerinin değişimi hareketli yük artışından sonra kontrol edilmiştir. Çift yönlü dişli döşeme, kiriş ve kolonlara uygulanan CFRP güçlendirme tekniğinin yapı rijitliği sünekliği ve deplasmanlarına etkisi değerlendirilmiştir. Yapının TBDY2018 yönetmeliği esaslarına göre güvenliği tesis edilmiş ve Covid19 aşı üretiminin ihtiyaç duyduğu hareketli yük kapasitesi olan 1000 kg/m2'ye göre CFRP'nin yapı elemanlarının eksenel basınç, eğilme ve kesme dirençlerine etkisi belirlenmiştir.

Anahtar Kelimeler: CFRP, betonarme yapılar, güçlendirme, kaset döşeme, deprem

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1. Introduction

Slab systems are the horizontal planes that must support both live load and dead loads. Waffle slab is two-way concrete slab reinforced by ribs in two direction and able to carry heavier loads ans span longer distances than flat slabs [1-3]. In other words, the waffle slab consists of frequent beams in two directions and the plate on them. Waffle slabs are generally used in projects where the column axis spaning is 7~8m and above (such as conference halls, shopping centres, industrial buildings) and in situations with high live loads (such as machine layout, truck loading area, forklift working area, storey car gallery). Larger spans can also be possible by using post-tensioning in this slab system.

The main beam and rib heights, plate thicknesses depend on the span, seismicity, material quality and load conditions. The bending moment and shear force of the ribs are calculated considering all parameters [1-3]. According to TBEC 2018 [4] the plate thickness shall not be less than 70 mm in reinforced concrete waffle slab systems under the effect of earthquake.

Fiber reinforced polymers materials are lightweight, noncorrosive, and exhibit high tensile strength. Composite materials with very different mechanical properties can be obtained by using different fiber and matrix materials. The advantages of carbon fiber can be listed as high modulus of elasticity and strength, low self-weight, resistance to chemical effects and high temperatures. It is known that the most application as a polymer matrix is with epoxy. The advantages of epoxy over other polymer matrices are high strength, high adhesion, and resistance to high temperatures [5-8].

Experimental and analytical studies on the retrofitting of reinforced concrete slab systems with CFRP are reviewed. Anıl et al. (2013) [9] They investigated the flexural behavior of a one-way reinforced concrete slab by opening it and reinforcing it with CFRP strips. It was seen that the method of strengthening one way reinforced concrete slabs with opening by using CFRP strips increased the load carrying capacity and stiffness of specimens considerably. Enochsson et al. (2007) [10] The work presented in this paper shows that CFRP sheets can be used to maintain and even increase the original load-capacity of two-way concrete slabs with openings. The aim of the study by Ghoroubi et al. (2020) [11] is to develop the retrofitting details, which will increase axial ultimate load capacity, stiffness, displacement ductility ratios, and energy dissipation capacities of short reinforced concrete (RC) low-slenderness columns to avoid adverse effects on earthquake performance. In the study by Emara et al. (2023) [12] the flexural behaviors of one- and two-way reinforced concrete (RC) slabs strengthened with carbonfiber- reinforced polymer (CFRP) strips under impact loads were investigated. In the study by Türer and Mercimek et al. (2023) [13-14] the effectiveness of a strengthening technique developed by using CFRP strips was investigated to prevent the punching strength loss caused by two square openings adjacent to the column in two-way reinforced concrete flat slabs and three different strengthening methods have been proposed to increase the punching strength of reinforced concrete (RC) flat slabs. Markou and Jung (2013) [15] Within this paper, the effects of CFRP plates on the strength of existing RC waffle slabs was investigated.

Earthquake is the heaviest loading situation that a structure encounters during its lifetime. It is known that due to insufficient ductility, insufficient strength and insufficient rigidity in reinforced concrete structures, damages occur under earthquake effect and even the structures reach the collapse point [16,17]. The parameters in the damage of existing structures or in reaching their carrying capacities can be listed as environmental impacts, increases in operating loads (dead, live, earthquake), changes in design regulations, etc. It is necessary for structural earthquake safety that all structures designed and constructed before the effective date of TBEC2018 [4] are checked according to the new conditions, the existing systems are evaluated and retrofitting works are carried out when required.

The subject of the study is to evaluate the increase of the vertical load capacities of the existing pharmaceutical production facility in Çorlu with a frame system using reinforced concrete two-way waffle slabs with CFRPs according to TBEC2018 [4] principles under varying operating loads. In the building where the application will take place, the live load bearing capacity has been increased from 750 kg/m^2 to 1000 kg/m^2 in order to realize the new functions created for Covid19 vaccine productions. The effect of CFRP reinforcement technique applied to waffle slabs, beams and columns on the stiffness, ductility and displacements of the structure was evaluated.

2. Analysis Of Existing Reinforced Concrete Structure And Earthquake Behaviour

The building was constructed in 2009 as a conventional frame reinforced concrete building according to TEC2007 [18] requirements in Çorlu, Tekirdag and is used as a pharmaceutical and vaccine production facility. Figure 1 shows the exterior view of the existing facility.

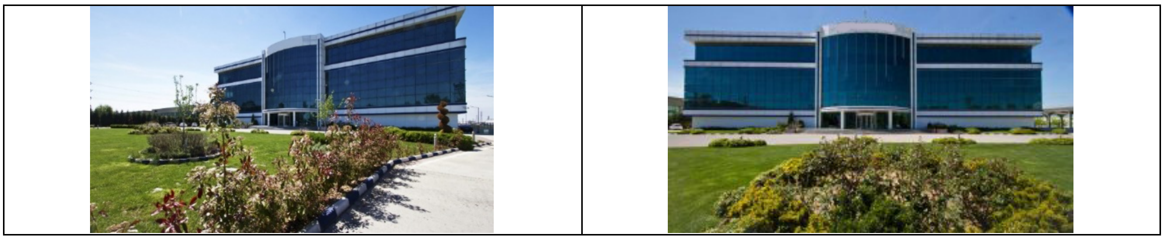


Figure 1. Exterior View of the Existing Pharmaceutical and Vaccine Production Facility

2.1. Architectural System

The building is 145m and 55m in size. It consists of 7 axis spans and 8 axes in X direction and 19 axis spans and 20 axes in Y direction. The axis span of the building is 7.86 metres in both directions. The building has 3 structural dilatations in Y direction and consists of 4 parts. There is a basement floor in the building. It is designed as ground + 2 floors. The total height of the building is 19.00m and the total height above ground is 12.00m. Figure 2 shows the ground floor layout and section view of the existing facility.

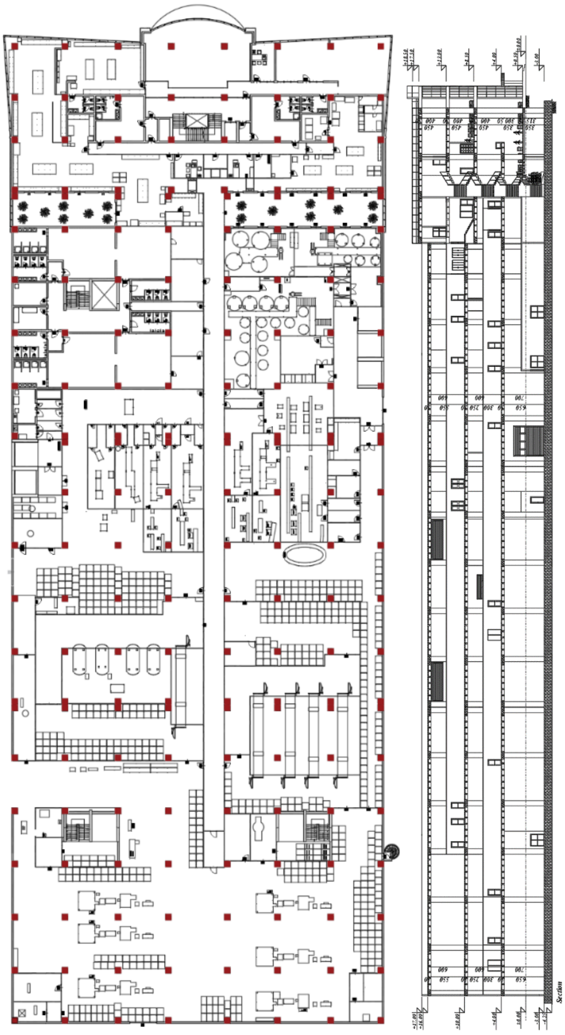


Figure 2. Ground Floor Layout and Section of the Existing Facility

Pharmaceutical and vaccination facilities are highly hygienic areas compared to other operations and are very sensitive to external factors. Architectural solutions and functions are very important in these facilities consisting of many different organisations. With the Covid19 pandemic, which started in 2019 and affected the whole world, vaccine production has started rapidly in this facility. With the urgent change of production, it is planned to change the operating loads in the building. For this reason, determination of the flexural strength capacity of the structure elements and earthquake performance analysis were requested.

2.2. Structural System

The structure is a reinforced concrete building with conventional frame system. All columns are 85x85cm square section and main bearing beams are 50cm x 100-115-125cm variable rectangular section. Two-way waffle slab is used on all floors. In the first design of the building, the live load was calculated as 750 kg/m^2 for the first two floors and analysed as 500 kg/m^2 for the attic floor. Figure 3 shows the mathematical model of the structure.

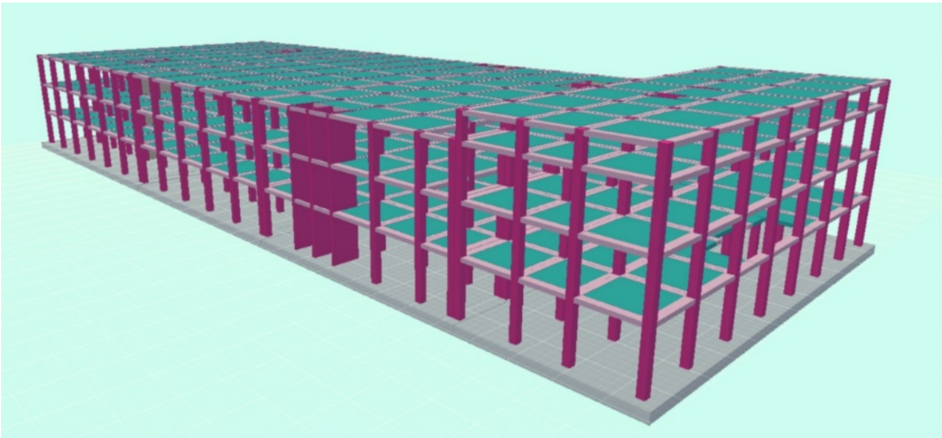
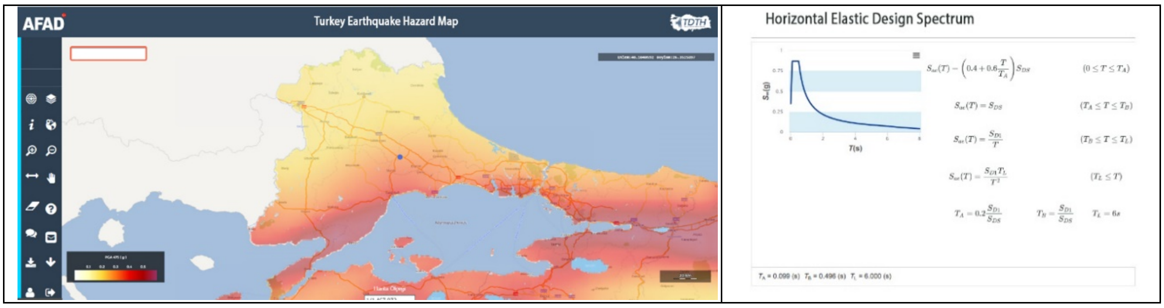


Figure 3. Mathematical Model of Structure

The existing static and architectural projects in the years when the building was built were reached. During the investigation, material information, foundation systems and soil parameters were analysed based on the existing project values and no studies were carried out on site.

According to TEC 2007 [18], the structure is accepted as a third-degree earthquake zone and the effective ground acceleration coefficient A_0=0.20g. For the specified soil type (ZD-Tight layers of sand, gravel, or very solid clay) and building coordinates, the maximum ground acceleration (PGA) was determined for DD-2 10% probability of exceeding in 50 years, corresponding to a return period of 475 years.as 0.293g from AFAD Turkey Earthquake Hazard Map Interactive Web Application [19] and analyses were performed with this acceleration value. The maximum ground speed (PGV) is 18.056 cm/sec. The coordinates of the existing structure are shown in the earthquake risk map and horizontal spectra are given in Figure 4.



(a) (b)

Figure 4. (a) Turkey Earthquake Hazard Map (b) Horizontal Spectra for Coordinates Where the Building Is Located

The building importance coefficient is I=1.0 for industrial buildings according to TBEC 2018 [4]. The building use categories coefficient is BKS=3. The building use categories is determined according to the building importance coefficient. While according to TEC2007 [18] the structural system behaviour coefficient of the building is R=7 in the current project, according to TBEC 2018 [4], the structural system behaviour coefficient is calculated as R=4 and the strength excess coefficient is calculated as D=2,5 [5].

3. Earthquake Performance Analysis and Retrofitting Project

Earthquake performance analyses were carried out according to the principles of the new building code for changing operating loads and new machine layouts planned to be added for Covid19 vaccine production. With the new machines and tanks to be added, the live load in the application areas has been determined as 1000 kg/m^2 and it is aimed to increase the vertical load capacity according to this load.

Determination of the earthquake performance of the structure Pushover analysis from linear inelastic methods was carried out. Thus, it is aimed to determine the performance level of the reinforced concrete building by performing the analyses required for the reinforcement decision if necessary. Earthquake calculation was made for both two directions in accordance with the building code TBEC 2018. The analysis and mathematical models of the structure were made in SAP2000 analysis program [20]. Figure 5 shows the three-dimensional models of the structure in SAP2000 [20].

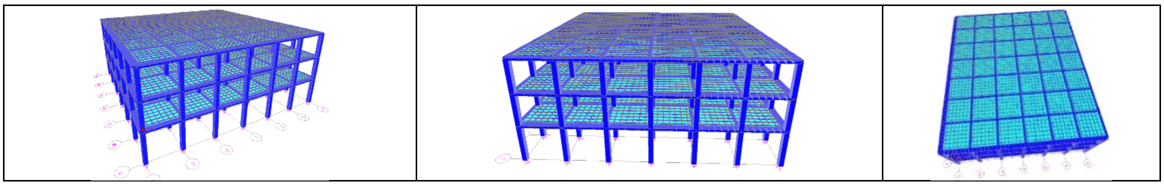
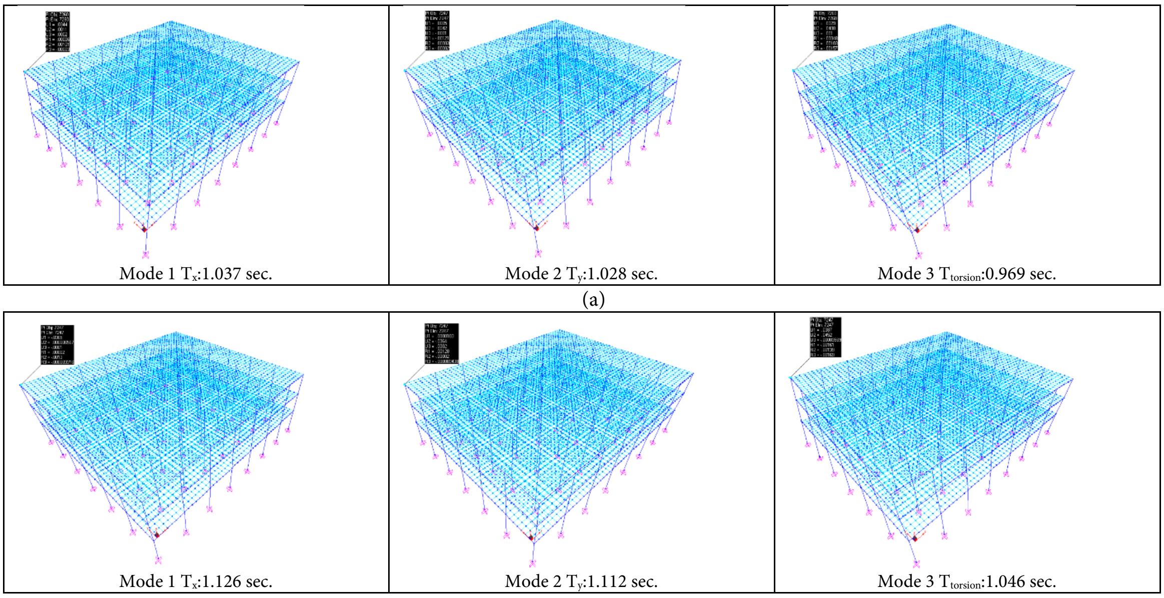


Figure 5. The Three-Dimensional Models Of The Structure in SAP2000

The 1st period is 1.037 sec. in X direction, the 2nd period is 1.028 sec. in Y direction and the 3rd period is 0.969 sec. in torsion mode at 750 kg/m^2 live load level. The 1st period is 1.126 sec. in X direction, the 2nd period is 1.112 sec. in Y direction and the 3rd period is 1.046 sec. in torsion mode at 1000 kg/m^2 live load level. The first three modes of the structure at 750 kg/m^2 and 1000 kg/m^2 live load level are given in Figure 6.



Mode 1 T_x:1.037 sec. Mode 2 T_y:1.028 sec. Mode 3 $T_{torsion}$:0.969 sec.

(a)

Mode 1 T_x:1.126 sec. Mode 2 T_y:1.112 sec. Mode 3 $T_{torsion}$:1.046 sec.

(b)

Figure 6. The first three modes of the structure (a) 750 kg/m^2 (b) 1000 kg/m^2

The maximum roof displacement of the structure in the X direction is 0.0365m for 750 kg/m^2 and 0.0409m for 1000 kg/m^2. The maximum roof displacement of the structure in the Y direction is 0.0364m for 750 kg/m^2 and 0.0384m for 1000 kg/m^2. Relative storey drift ratio in both directions (X-Y) increased from 1.20% to 1.40%. The relative storey drifts of the structure with both live loads are shown in Figure 7.

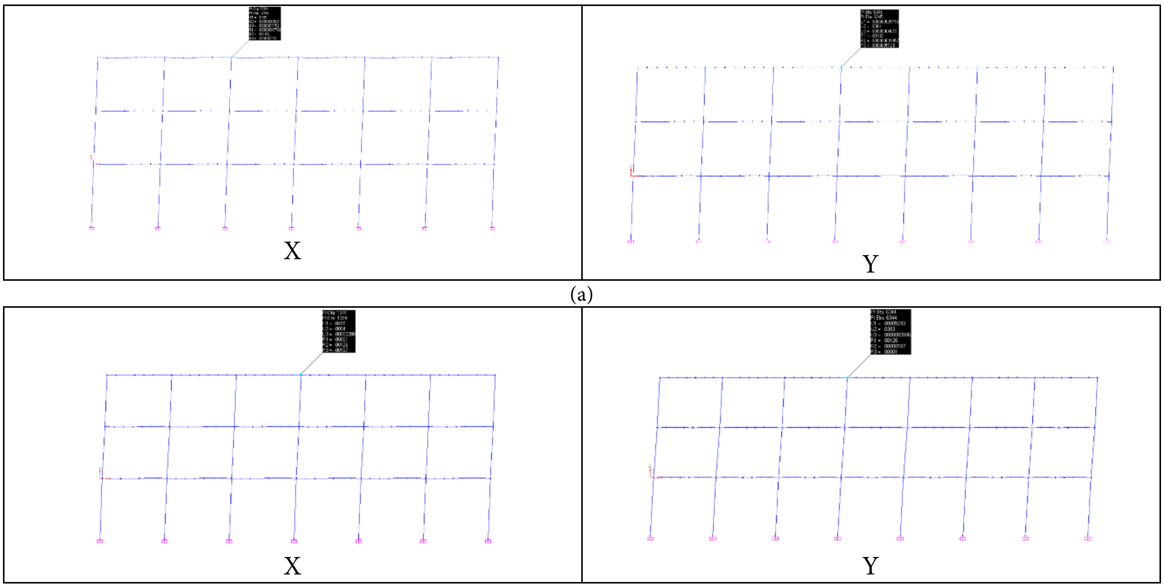


Figure 7. The relative storey drifts of the structure (a) 750 kg/m^2 (b) 1000 kg/m^2

The natural vibration periods for 750 kg/m^2 live load, storey displacements, base shear forces and relative storey drifts for both earthquake directions were determined. The values obtained are within the limits of the TEC2007 [18]. Then the same values were determined for 1000 kg/m^2 live load value of the structure. There was a small increase in the natural vibration periods of the existing structure, but there was no change in the mode shapes in terms of direction. The base shear forces increased from 1307 tons to 1524 tons for both directions. Relative drift ratios increased from 1.2% to 1.4% for both directions. However, the relative storey drifts ratios are within the limits of both the TEC2007 [18] and TBEC2018. The earthquake performance of the building according to TEC2007 [18] ensures the life safety performance target. Figure 8 shows the earthquake performance level of the structure.

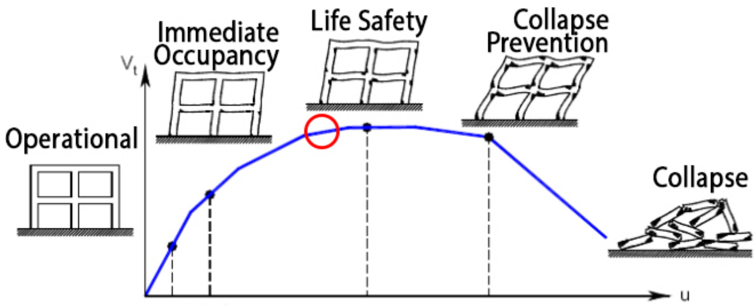


Figure 8. The Earthquake Performance Level of the Structure

The vertical load capacity of the waffle slabs, beams and columns should be increased on an element basis in the retrofitting of the structure. Providing the relative drift limits in the current regulation shows that the structure needs an increase in vertical load capacity rather than an additional increase in horizontal stiffness. CFRP applications generally contribute to the increase in strength and ductility of structural elements. CFRP applications do not cause a significant increase in the horizontal stiffness of the structural elements. Traditional reinforced concrete shear wall additions and jacketing significantly increase the stiffness of the structure. Since there is no need for stiffness increase in the investigated structure, a method using CFRPs is proposed to increase the vertical load capacity and ductility of the structure. Within the method, bending and shear strengths of waffle slabs and beams will be increased on element basis. In addition, it is aimed to increase the axial load carrying capacity and shear capacity of the columns with CFRP wrapping.

In order to increase the flexural strength capacity, a sample main reinforced concrete beam was selected, and its numerical values were given within the scope of the study. The width of the selected beam is 125cm, the total height is 50cm, the plate thickness is 10cm and the width of ribs are 20cm.
After linear and nonlinear static analyses, the maximum moments at the span of the main bearing beams were calculated and compared with the beam flexural strength capacities. The moment values in the beams are

given in Table 1. The M_{DL} (kNm) moment is the moment consisting of the dead load, M_s (kNm) is the service moment at section and M_u (kNm) moment is the factored moment at a section.

Table 1. Moment Values of Main Beam

Live Load	M_{DL} kNm	M_s kNm	M_u kNm
750 kg/m²	147	373	511
1000 kg/m²	147	427	584

As a result of the analyses and calculations, it was determined that the flexural strength capacity of the beam was insufficient by increasing the live load. In the factory where vaccine and pharmaceuticals are produced, the alternative of retrofitting with CFRP was preferred due to its fast and clean construction technique. CFRP strips and fabrics were used to increase the shear force and flexural strength capacities in reinforced concrete main bearing beams, rib and plate slabs, columns.

Table 2. Technical Properties of Reinforced Concrete Beams

fc' (N/mm²)	30
fy (N/mm²)	420
As (mm²)	3012
Modulus Of Elasticity of Concrete (N/mm²)	32000
Modulus Of Elasticity of Steel (mm²)	200000
k (ratio of depth of neutral axis to reinforcement depth measured from extreme compression fiber)	0,334 (ACI 318-05) [21,22]

The technical properties of the CFRP fabric used are given in table 3 and the technical properties of the CFRP strips are given in table 4. These values were used in the application and retrofitting calculations.

Table 3. Technical Properties of CFRP Fabric

Modulus Of Elasticity (N/mm²)	230000
Type of Fiber	High Strength Carbon
Tensile Strength (N/mm²)	4900
Elongation at Break (%)	2,10
Thickness S (mm)	500
Mass Of the Fabric Per Unit Area (g/m²)	300
Reaction to Fire	Classe F

Table 4. Technical Properties of CFRP Strips

Modulus Of Elasticity (N/mm²)	165000
Tensile Strength (N/mm²)	3000
Elongation at Break (%)	1,5
Thickness S (mm)	1,2
Width (mm)	50
Cross Section Area (mm²)	60

As a result of the retrofitting calculations, static and reinforced concrete analyses were repeated in order to increase the vertical load capacities under increased operating loads and the retrofitted section was checked for shear force and flexural strength capacities. The retrofitted section is capable of sustaining the new flexural strength ΦM_n =615,8 kNm. This value is sufficient in terms of operational and earthquake safety.

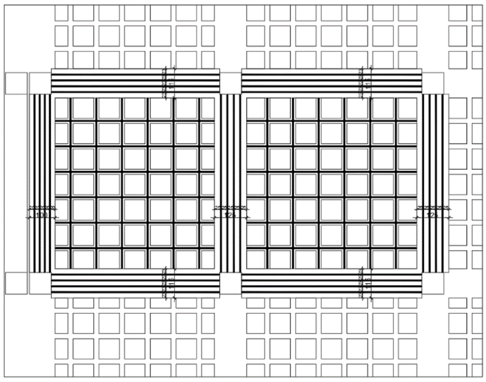
The maximum shear force of the beam was calculated as V_u=887 kN. Reinforced concrete beams are planned to be wrapped in U-shape with CFRP fabrics and will be anchored to the beam with CFRP anchors. The retrofitted section is capable of sustaining the new shear strength V_s=1067,9 kN. This value is sufficient in terms of operational and earthquake safety. After the increase in live loads and retrofitting with CFRP, it was observed that the performance level of the structure ensured the life safety performance level according to the TBEC2018 [4].

3.1. Retrofitting application

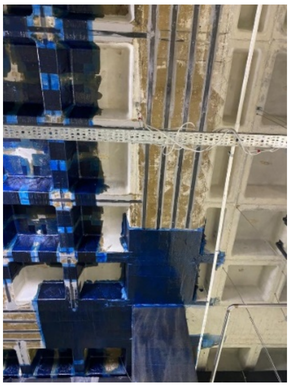
Cross-sectional bearing capacity checks of all reinforced concrete structural elements were carried out and reinforcement projects were prepared for changing fast operating loads. CFRP reinforcement was preferred due to the urgency of Covid19 vaccine production. The details of the second-floor reinforcement project are given within the scope of the study according to the tank and machine layouts planned to be added.

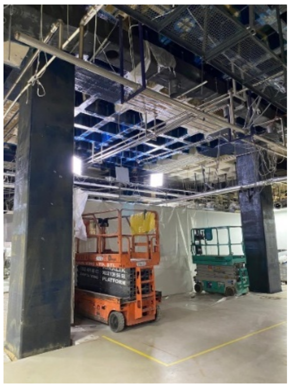
Firstly, the area to be retrofitted was cleaned and separated from the other parts of the facility. The retrofitting application was completed with minimal intervention in the ultra-hygienic facility, which is the subject of the study. Before the application, plaster, paint etc. were removed from the reinforced concrete elements and the application started.

CFRP strips were used in both directions to increase the flexural strength capacities of the second-floor reinforced concrete ribs and beams. 4 strips were used in both directions in the beams and 1 strip in all ribs. Figure 9 shows the CFRP strips reinforcement application on beams and ribs.



(a)



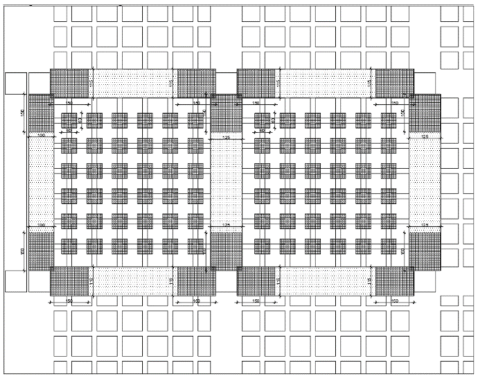


(b) (c)

Figure 9. Second Floor CFRP Strips Reinforcement (a) Project Layout (b, c) Application Area

The beams were wrapped with a single layer of CFRP fabric along the entire beam to increase both shear force and flexural strength capacities. 2 layers of wrapping were made in the first 150cm in the column-beam joints, which are the plastic hinges that may occur. CFRP fabrics were wrapped u-shaped on the beams and ribs and anchored to the existing reinforced concrete elements. U-shaped fabrics were applied from the bottom of the ribs towards the plate. CFRP fabrics was wrapped and anchored at the ribs as 60cm in both directions. Thus the shear force capacity of the beam and all ribs is increased for varying operating loads. Figure 10 shows the CFRP fabric application for the shear force capacities of beams and ribs.

In order to increase the load bearing capacities of all columns in the frame where the operating loads will increase, wrapping with CFRP fabric was applied. The columns were wrapped in 3 layers in the first and last 75cm by removing the ground concrete by 15cm. In the parts where the probability of plastic hinge occurred is high and where the largest moments are calculated, the columns were wrapped in 3 layers. The columns were wrapped in 2 layers in the remaining area. Figure 12 shows the CFRP fabric application for the load bearing capacities of columns.



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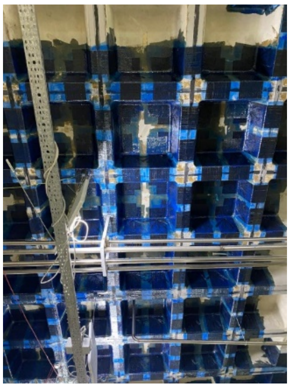
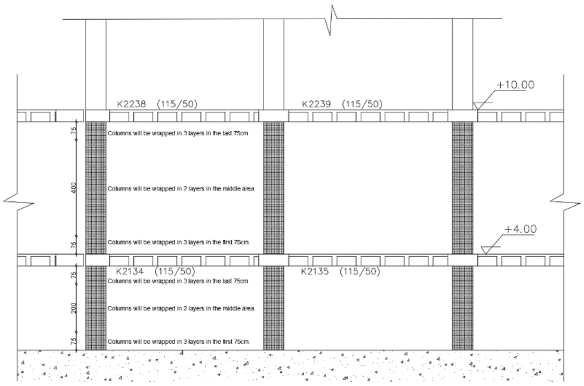



(b) (c)

Figure 10. Second Floor CFRP Fabric Reinforcement (a) Project Layout (b, c) Application Area



(a)


(b) (c)

Figure 12. Second Floor CFRP Fabric Reinforcement (a) Project Section (b, c) Application Area

4. Conclusion

Waffle slab is two-way concrete slab reinforced by ribs in two direction and able to carry heavier loads ans span longer distances than flat slabs. The use of two-way waffle slabs is quite common in reinforced concrete framed factory buildings where the spans to be passed and the live loads are high.

The selected sample building is a reinforced concrete framed industrial building with two-way cassette flooring. In the building where the application will take place, the live load bearing capacity has been increased from 750 kg/m^2 to 1000 kg/m^2 in order to realize the new functions created for covid19 vaccine productions. Firstly, in the structural model, the building characteristics such as natural vibration periods, relative storey drifts, lateral stiffnesses, base shear forces and mode shapes were determined. After the increase in live load, these values were determined again and examined within the scope of both TEC2007 [18] and TBEC2018 [4]. The 1st period is 1.037 sec. in X direction, the 2nd period is 1.028 sec. in Y direction and the 3rd period is 0.969 sec. in torsion mode at 750 kg/m^2 live load level. The 1st period is 1.126 sec. in X direction, the 2nd period is 1.112 sec. in Y direction and the 3rd period is 1.046 sec. in torsion mode at 1000 kg/m^2 live load level. When the horizontal earthquake spectra in both TEC2007 [18] and TBEC2018 [4] were analyzed, it was observed that the earthquake loads on the structure tended to decrease since the period of the structure remained in the decreasing section in these spectra. Relative storey drift ratio in both directions (X-Y) increased from 1.20% to 1.40%. The base shear forces increased from 1307 tons to 1524 tons for both directions.

In its current condition (750 kg/m^2), the earthquake performance of the building was found to ensure life safety according to TEC2007 [18]. When the loads of the structure reached 1000 kg/m^2, the necessary parameters were checked and it was determined that after the strengthening with CFRP, it reached the target life safety performance level according to TBEC2018.

In reinforced concrete buildings with special architectural functions such as pharmaceutical facilities, fiber polymer reinforcement was preferred over traditional methods on the sample building due to its fast construction technique, clean application and no change in cross-section. Due to the increasing operating loads, the existing load-bearing elements were reinforced with CFRP (fabric and strip). CFRP strip was used to increase the shear force and flexural strength capacities of beams and ribs in frames where live loads will increase.

While CFRP do not make a significant contribution to the lateral stiffness of structural elements, they provide a significant increase in axial strength, shear strength and flexural strength with the wrapping effect. The maximum moment increase for the sample beam was calculated as 13% with the change in live load. The retrofitted section the new flexural value is sufficient in terms of operational and earthquake safety. The maximum shear force of the beam for increasing live loads was calculated and it was determined that the reinforced section remained within the limits of the new shear strength capacity. CFRPs also contributed significantly to the increase in element ductility in the sample project. And it allowed the structure performance to remain within the appropriate conditions.

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Conflict of Interest Statement

The authors declare that there is no conflict of interest.

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