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INVESTIGATION OF THE SEISMIC BEHAVIOR OF BUILDINGS WITH U-BOOT SLABS

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Abstract

Since U-boot slabs can cover a large area without the need for columns, they are known as a favorable option for architects. On the other hand, from the point of view of the structural and earthquake engineer, reducing the number of columns can lead to the reduction of the additional resistance factor of the structure, which may lead structures to risks during an earthquake. Considering that published comprehensive studies in this field are limited, therefore, in this paper, the nonlinear dynamic behavior of concrete structures with U-boot slabs will be investigated. For this purpose, the behavior of short to medium-order structures will be investigated. Correspondingly, based on the obtained results, the necessary recommendations in this field will be proposed to improve this system. These recommendations are proposed with the approach of architectural requirements as well as structural requirements.

Keywords: Concrete building; U-boot slab; Flexural; Seismic behavior; Pushover.

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1 INTRODUCTION

Generally, architects are always looking for a solution to reduce the number of columns and use more space, especially for commercial uses and parking. Reducing the number of columns improves the architectural aspects which are usually in conflict with the structural engineering approach, especially for Reinforced Concrete (RC) buildings. Till now, several methods such as special truss frames [1], staggered trusses system [2], tube framing for perimeter columns [3], and the use of waffle slabs have been introduced to improve the use of space by reducing the number of columns. Among the proposed methods, using waffle slabs can be considered as a practical and economical use for RC buildings. The U-boot slabs as a waffle slab system introduced by Robert-II Grande, an Italian engineer, who developed and patented a new system of hollow former to reduce transport vehicles [4]. It is the recycled polypropylene formwork technology used for construction purposes. One of the important barriers with constructions, in the instance of horizontal slabs, is the soaring weight, which ceiling the span. Figure 1 shows an example of an industrial U-boot and the schematic view of the U-boot slab system. In U-boot automation, slabs are fabricated with large spans a contract floor thinner by depleting the weight while keeping the advance of reinforced concrete technology.

Although the use of the U-boot slab increases the useful space of the architecture, due to the reduction of the number of columns and also the lack of use of middle beams, comprehensive studies should be done regarding its seismic behavior. In fact, the RC frames as conventional seismic resisting rely on the hinge formation at two ends of beams to dissipate imposed seismic energy. Since the beams as a part of the main frame at the moment resisting frame (MRF) has the task of bearing gravity loads in addition to lateral loads, it is difficult to repair it after a severe earthquake. Consequently, in this paper, the behavior of structure with U-boot slabs is considered.

U-Boot®
U-Boot® Beton void box for two-way lightened slabs (https://www.daliform.com)

Figure 1: An example of a U-boot and the U-boot slab system.

2 NUMERICAL STUDY

2.1 Modeling approach

To analyze the numerical models, ETABS [5] software was used. The structural elements are modeled as nonlinear frame elements with lumped plasticity by defining plastic hinges at both ends of the beams and columns. Figure 2 depicts the hinge type and location. ETABS [5] incorporates the plastic hinge properties described in FEMA 356 [6] and as shown in Figure 3 [6], the points labeled A, B, C, D, and E define the force-deformation behavior of a plastic hinge. Once the structure is modeled and the section properties, steel content, and applied loads are specified, the plastic hinges are assigned to the structural elements (P-M and V for columns, M and V for beams, and M and V for shear links), where V stands for shear plastic hinge, M represents flexural plastic hinge, and P-M stands for the axial-flexural hinge.

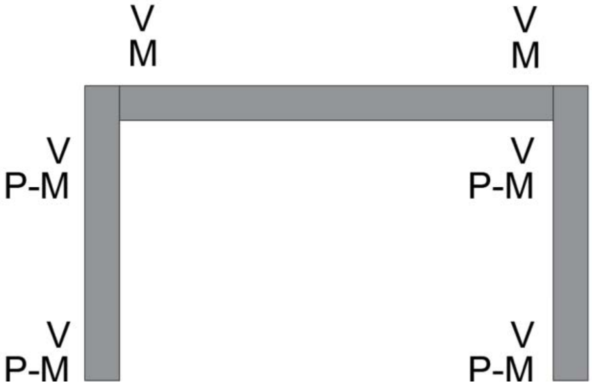


Figure 2: The hinge type and location.

The user-defined hinge properties are obtained via moment-curvature analysis of each element. The modified Park model [7] for confined concrete and the typical stress-strain model with strain hardening for steel are implemented in moment-curvature analyses. The sensitivity of a plastic-damage-based structural damage index on mesh density was studied by Kang and Lee [8]. The moment-curvature analysis is carried out for each column, considering the section properties and constant axial loads on the elements. All actions shall be classified as either deformation controlled, or force-controlled using the component force versus deformation curves based on FEMA 440 [9]. Since columns are controlled as force control components, this rule is applied to columns. In Figure 3, points B and C are related to yield and ultimate curvatures, respectively. Point B is obtained from ETABS using an approximate value for the component's initial effective stiffness according to ATC-40 [10] (i.e., 0.5EI and 0.70EI for beams and columns, respectively). Also, the ultimate curvature is described as the smallest values of a) reduced moment equal to 80% of the maximum moment determined from the moment-curvature analysis, b) extreme compression fiber reaching the ultimate compressive strain of concrete based on FEMA 440 [9], and the longitudinal steel reaching a tensile strain equal to 50% of the ultimate strain capacity that corresponds to the monotonic fracture strain.

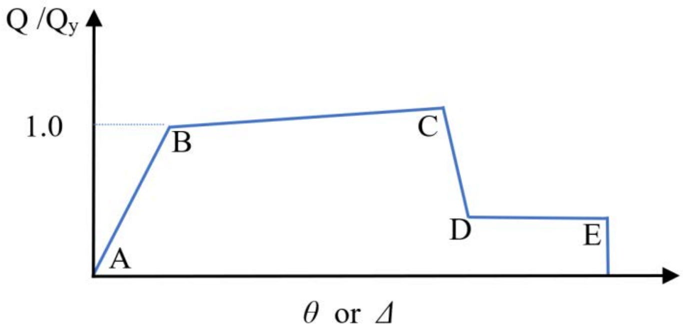
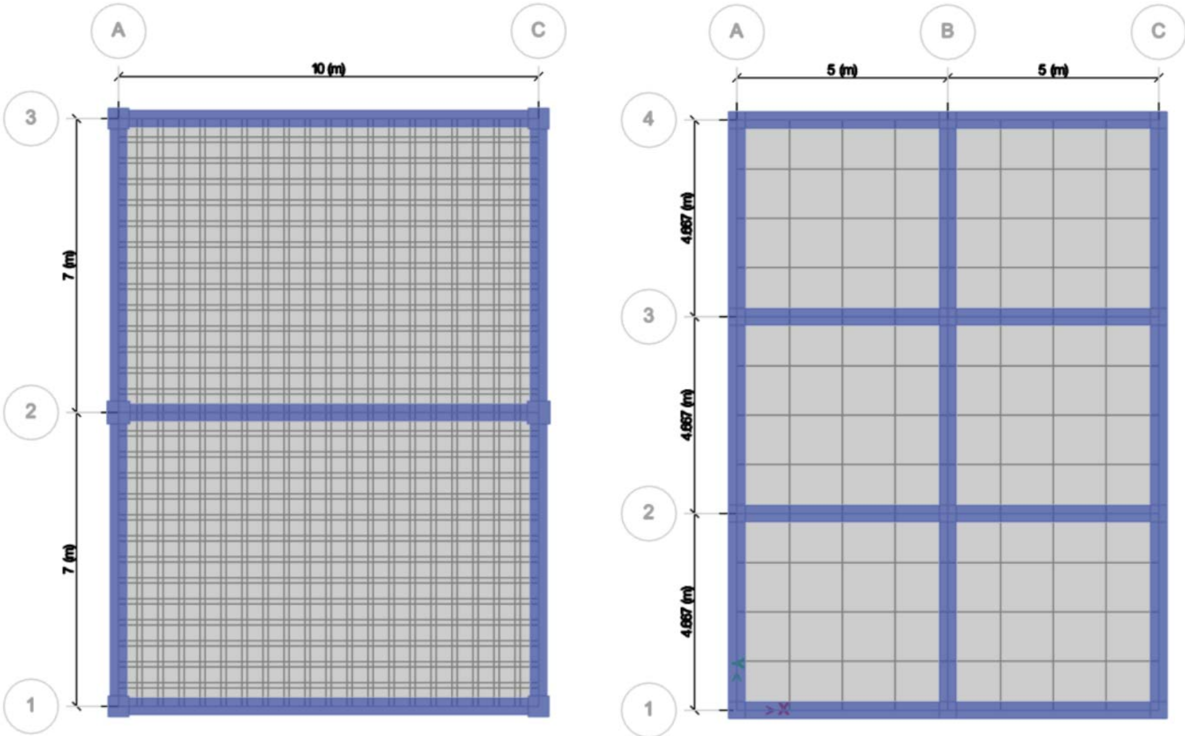


Figure 3: Generalized force-deformation relation.

All models are subjected to lateral loads that are gradually increased from zero to a magnitude beyond the system's capacity. The maximum displacement limit is considered to occur at a drift angle of 2.5% per ASCE 7-16 [11]. Also, based on the ASCE [11] and FEMA 440 [9], the maximum ultimate strength degradation is considered as 20%. Therefore, the final acceptable amount of the system bearing will be calculated as the minimum amount of 2.5% drift or 80% of ultimate strength degradation.

2.2 Numerical models

To evaluate the behavior of the buildings when the U-boot is used for the slab, a plan with the dimension of 10m×14m is considered, Figure 4. Accordingly, the placement of the columns as well as the framing plan is shown in Figure 5. For buildings with two-way slabs, a thickness of 150mm was designed for the slab. Also, the thickness of U-boots was designed according to the distance of the boots and the slab's rebar.



(a) (b)

Figure 4. The plan view of structures with a) U-boot slab, and b) two-way slab.

Also, three types of structures including structures with 3 stories, 6 stories, and 9 stories are investigated which are shown in Figure 5. The structures were designed based on the ACI [12]. For the design of the structures, the dead and live load equals, respectively, 105 and 200 kg/m^2 were considered. Also, the weight of slabs was considered using the capability of the software. Also, a load of 800 Kg/m for each story and 300 Kg/m on the premises of structures was applied to the structures as equivalent to walls.

3 story	6 story	9 story

Two-way Slab

U-boot slab

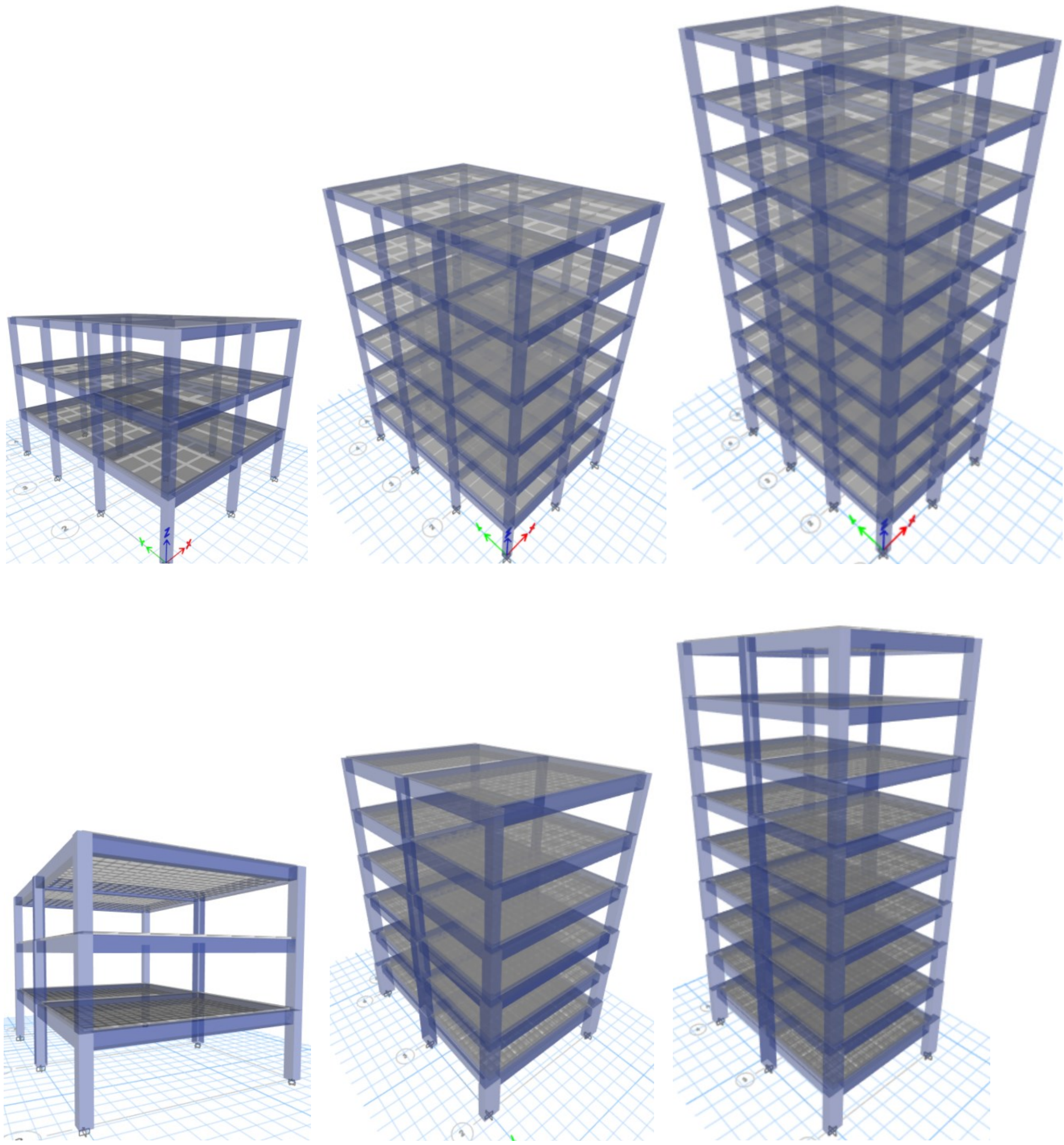


Figure 5: The view of the studied structures.

Moreover, to determine the lateral load imposed on the structures, a spectrum analysis was used. To do so, the spectrum as shown in Figure 6 according to the Iranian Code 2800 [13] was used for this purpose. It was assumed that these buildings are built on type II soil in an area with high seismic risk.

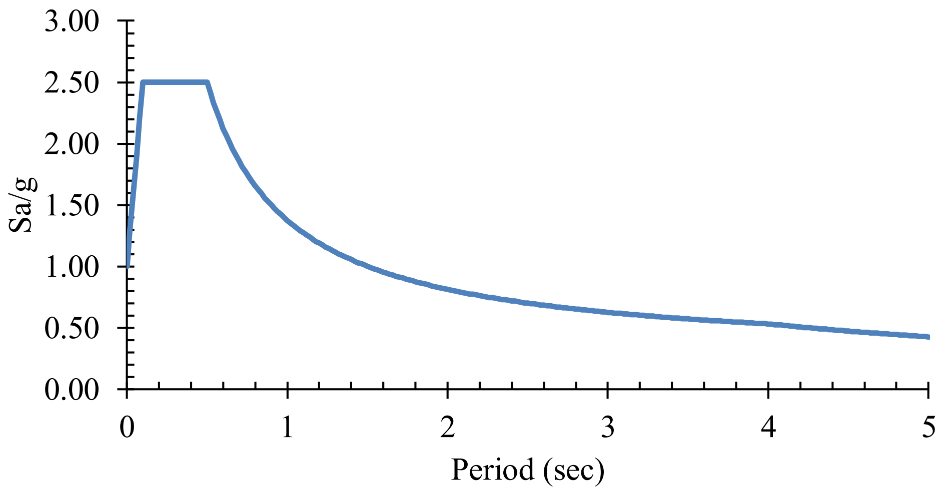


Figure 6: The spectrum used in the design of structures.

3 RESULTS AND DISCUSSIONS

3.1 Fundamental period

As the fundamental period, T, for each structure is accounted as an important parameter in the design of structures as well as in predicting the behavior of structures, the T of structures in two directions is listed in Table 1. Referring to the results of this table, in low-rise structures (three stories), by changing the floor from a two-way slab to a U-boot slab, the fundamental period of the structure decreases, but in 9-story structures, this trend is reversed. The main reason can be stated that by changing the floor and reducing the number of columns, columns with huge dimensions are inevitably used, which has a significant effect on the fundamental period. So, a comprehensive study with a wide number of structures must be accomplished to consider the effect of changing the floor from a two-way slab to a U-boot slab, on the fundamental period. By the way, in low-rise structures, the U-boot reduces the fundamental period.

Model	T_x	T_y	U/RC	
			T_x	T_y
RC-3	0.574	0.51		
RC-6	0.951	0.84		
RC-9	1.081	1.07		
U-3	0.562	0.52	0.98	1.02
U-6	0.812	0.75	0.85	0.90
U-9	1.33	1.17	1.23	1.09

Table 1: Comparing the fundamental period of structures.

3.2 Pushover curves

Pushover curves give valuable information about the behavior of the structure. The general features of each system can be realized by an overall review of the diagram. Therefore, the pushover curves of the system are compared in Figure 7. Results indicated that systems with U-boot slabs have a failure before reaching the maximum allowed drift. Therefore, it is expected to fail the structure with low ductility. Therefore, it is susceptible to damage in high-risk seismic zones. The structural parameters obtained from the curves are investigated in the next section.

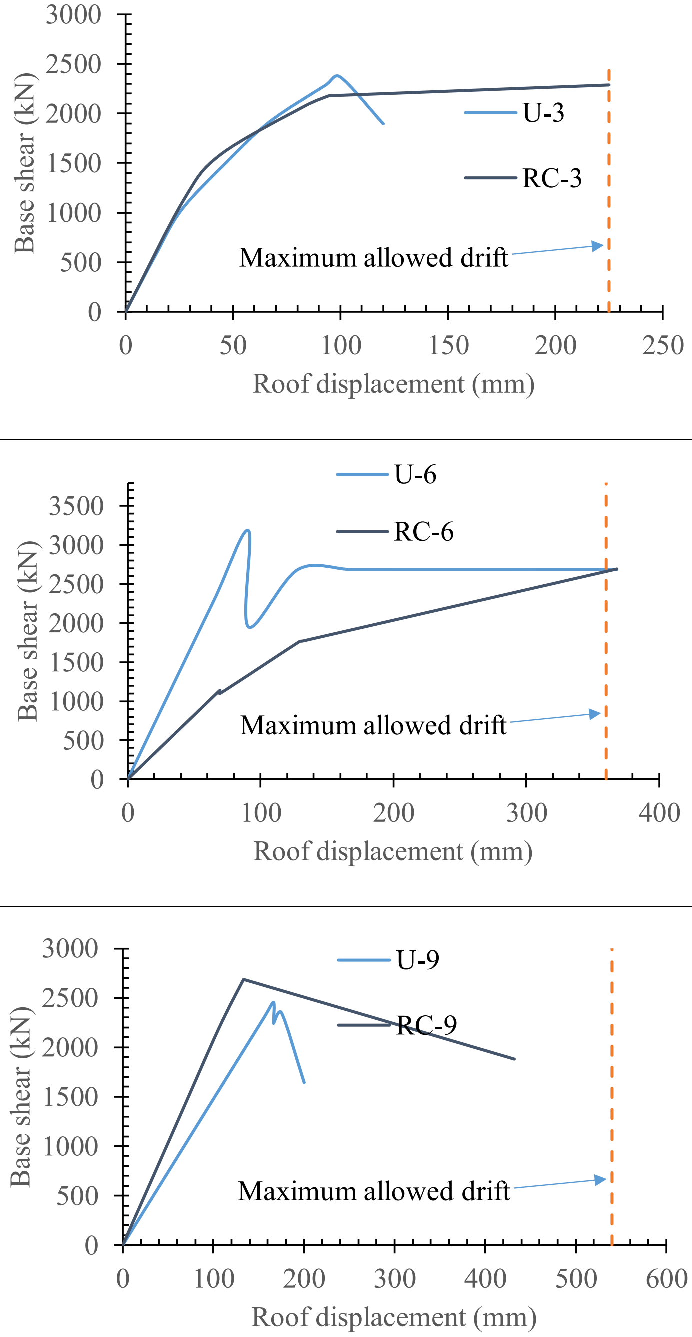


Figure 7: The pushover curves.

3.3 Structural parameters

In Table 2, the structural parameters of the models are listed. Results indicate that using U-boot slabs the displacement corresponding to the yielding, Δ_y, is reduced for low-rise structures although it increased in higher structures. But, it causes a reduction in the ultimate displacement, Δ_u, by 36%, 63%, and 22%, respectively, for structures with 3, 6, and 9 stories.

In the 6-story structure, although the pushover curve reaches the maximum allowed drift, the ultimate displacement is measured at the point of the dropped curve corresponding to the 80% ultimate strength. This result causes a reduction in the ductility, μ, by 0.52%, 0.46%, and 0.48%, respectively, for structures with 3, 6, and 9 stories. This reduction in μ is considerable. Comparing the ultimate lateral strength of the structures indicated that the system with two-way slabs and U-boots shows a close outcome together with differences between 4% to 19% that is despond of the dimensions of the columns. But, the remarkable finding regarding the overstrength, Ω, is that the use of U-boots has increased it in three-story structures, but it has decreased by 48% and 15% in 6-story and 9-story buildings, respectively.

Model	Δ_y (mm)	Δ_u (mm)	V_y (kN)	V_u (kN)	μ	Ω
RC-3	35.06	225.00	1464.16	2288.73	6.42	1.56
RC-6	66.28	225.00	1087.81	2689.67	3.39	2.47
RC-9	105.58	225.00	2183.67	2685.68	2.13	1.23
U-3	32.35	99.84	1299.32	2371.07	3.09	1.82
U-6	70.45	128.06	2502.06	3188.11	1.82	1.27
U-9	158.26	175.08	2335.72	2452.65	1.11	1.05
	0.92	0.44	0.89	1.04	0.48	1.17
U/RC	1.06	0.57	2.30	1.19	0.54	0.52
	1.50	0.78	1.07	0.91	0.52	0.85

Table 2: Structural parameters.

4 CONCLUSIONS

In this paper, the effect of U-boot slabs on the behavior of RC frames was numerically investigated. The findings are summarized in the following:

- The U-boot gives a better architectural aspect than the two-way slab. It is due to the long span used and the greater spaces when the U-boots are used.
- In low-rise structures, by changing the floor from a two-way slab to a U-boot, the fundamental period of the structure decreases, but in 9-story structures, this trend is reversed.
- Pushover curves results indicated that systems with U-boot slabs have a failure before reaching the maximum allowed drift.
- Using U-boot slabs the displacement corresponding to the yielding, Δ_y, is reduced for low-rise structures although it increased in higher structures. But, it causes a reduction in the ultimate displacement, Δ_u, by 36%, 63%, and 22%, respectively, for structures with 3, 6, and 9 stories. In the 6-story structure, although the pushover curve reaches the maximum allowed drift, the ultimate displacement is measured at the point of the dropped curve corresponding to the 80% ultimate strength.
- Since the systems with U-boot slabs show a lower ductility, they are susceptible to damage in high-risk seismic zones. U-boot slabs cause a reduction in the ductility, μ, by 0.52%, 0.46%, and 0.48% %, respectively, for structures with 3, 6, and 9 stories. This reduction in μ is considerable.

- Comparing the ultimate lateral strength of the structures indicated that the system with two-way slabs and U-boots shows a close outcome together with differences between 4% to 19% that is despond of the dimensions of the columns.
- Regarding the overstrength, Ω, the use of U-boots has increased Ω in 3-story structures, but it has decreased Ω by 48% and 15% in 6-story and 9-story buildings, respectively.

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