Realistic Determination of Live Loads on Various Reinforced Concrete Structures

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Abstract-This paper presents various case studies of examined and calculated live loads on reinforced concrete structures. These case studies accumulated information and data of existing structures about their design live loads and acquired detailed drawings showing the reinforcement in their floor slab sections. The actual occupancy loads that act on the floor slabs were assessed, and the ultimate loads that an individual slab section should be able to support were calculated using the methods recommended by ACI, CP-114, CP-110, and the yield line theory. A reinforced concrete slab panel was also tested to check the validity of the theoretically predicted ultimate loads. The results were compared to find a safety margin and, if necessary, recommend lower live load outlines for cost reduction. The case studies showed that there is sufficient margin to reduce design live loads on the floor slabs of residential buildings, especially in multistory apartment blocks. Moreover, it was found that the live loads, especially on residential buildings, could be decreased to two-thirds of the code values without risking floor overloading.

Keywords-structures; loads; economy; case study; occupancy; slab; reinforcement

I. INTRODUCTION

Generally, loads are classified as dead loads, live loads, including people, supplies, and machines, environmental loads, including rains and snow loads, lateral loads, such as wind and blasts, dynamic loads due to earthquakes, upward loads, such as those due to water, earth pressure, waves, and ice, and loads induced by temperature and shrinkage [1]. Among these, dead loads can be determined with a high degree of certainty. Snow and rain loads are very rare in Pakistan. The wind has a pronounced impact on tall buildings having more than 10-15 stories and has little significance in public or common residential buildings [2, 3]. Using the maximum possible values given by the standards for the loads increases construction costs [4, 5]. For these reasons, probabilistic considerations are used to determine design loads. Moreover, the design values of live loads are very rarely reached during the life spans of many structures [6, 7]. The load values are usually based on recommendations of foreign standards, which are very conservative compared to the actual live loads on floor slabs in Pakistan. Therefore, more realistic live loads should be determined for the design of the structures. Assuming that a typical person weighs 68kg and occupies a space of $0.37m^2$, it has a live load of about $185kg/m^2$. People can be overloaded to produce a maximum load of $610kg/m^2$. However, such occupancy in a large area is very unlikely. Another factor that also affects the decision regarding the intensity of live loads is that the probability of achieving the full design live loads on an entire floor decreases as its area increases. To incorporate this fact, building codes suggest live load reductions. One common way to achieve this is to reduce live load values for areas larger than $14m^2$ at a rate of 0.08% per m^2 up to a reduction of 60% [8, 9], but this reduction does not apply to public assembly buildings. Certain types of live loads may produce dynamic effects. However, more commonly, these are not considered explicitly, since a complete analysis would be excessively time-consuming [10, 11]. The live loads are conservative enough to account for increased stresses caused by the structure's vibration [12-15].

II. PRESENT INVESTIGATION

A combined effect of both load enhancement and the safety factors of the materials allows a structure to withstand the imposed loads, which could vary even several times more than

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the loads for which it was intended [16]. The safety factor ensures that a reasonable margin exists between the maximum operating load of the component and its load capacity. It has been common practice to introduce idealization, approximation, and larger bending moments based on conventional methods to design structures for a long time, increasing safety margins. Although incidental overload can occur, the question arises of whether it can be possible to accommodate such massive loads to exhaust all the strength of the floor [17]. A reliability analysis exhibits an almost infinite load on a slab in monolithic connections with the structural members for its complete collapse. As an example, on the eve of the cricket World Cup celebration, it was observed that a balcony of a house having dimensions of 1×5m was jam-packed with almost 30 people. The people were weighing 2040kg approximately, which is equivalent to 458kg/m^2. From the technical details of the slabs, the ultimate load-carrying capacity was calculated to be about 3,806kg/m^2. Nevertheless, this is one case of the overloadings that must be considered while proposing a realistic value of live loads. For this reason, the ACI code recommended a live load of 488kg/m^2 for balconies and a minimum of 293kg/m^2 when the area of the balcony of a residential building does not exceed 9m^2 [18, 19].

This study examined a wide variety of existing Reinforced Cement Concrete (RCC) buildings in different towns and cities of the Sindh province in Pakistan, including primary and secondary schools, urban and rural hospitals, mosques, residential villas, luxurious apartments, and multistory shopping centers and malls. Technical data of buildings in terms of slab thickness, size, spacing, and arrangement of reinforcement bars were obtained, and the intensity of live loads acting on these slabs was assessed. The ultimate live loads were calculated by employing the methods recommended by ACI [17], CP-114 [18], CP-110 [19], and yield line theory. A yield value of 275MPa was adopted for steel. Wherever the principles of Limit State Design were applied, the partial safety factors for loads were presumed to be equal to unity. The bending moment factors for the calculations were selected from the respective design standards' tables wherever appropriate. A wide variety of chosen case studies are presented in the following sections [23-25].

A. Multistory Building

This building was under construction during the investigation. The structural frame with floor slabs was already complete while dividing masonry walls were being erected. There was a large stack of bricks on the first-floor slab, soaked with water. The stack was approximately 1.5m in height and consisted of about 1000 bricks weighing about 3,450kg. The room's total area was 12.25m^2 (3.5×3.5m). Adding the weight of 6 workers and 2 visitors, which is about 545kg, the total imposed load on the floor area was equal to 326kg/m^2. This is much higher than the design live-load of 145kg/m^2. However, from technical data, the slab was reinforced with main bars of 13mm diameter placed at 150mm c/c and distribution bars of 10mm diameter placed at 230mm c/c. The minimum standard load-carrying capacity, shown in Table I, was 1,693kg/m^2, which is 5.3 times more than the actual imposed load. Thus, there is a possibility of reducing the design live-load without risking the stability and durability of the structure. It is expected that the actual occupancy loads of this flat, under normal circumstances, would not be more than the Villa's [26-27].

B. Residential Villa

The residential Villa was a double-story building that was assessed to have a total live load of 455kg, including all items of daily use, on a total floor area of 21m^2. This can be compared with the lowest live load of 1450kg/m^2 calculated based on the elastic theory method and the recommendations of CP-114. This building had a considerable inherent margin of safety. Even in occasional overload due to visitors on a festivity, the load will never touch the ultimate mark of 1665kg/m^2 calculated based on CP-110. Therefore, there is enough margin to reduce the design live loads by reducing reinforcing steel and cost without sacrificing safety.

C. Vocational Training Center

This building was a women's vocational training center with large halls occupied by professionals and trainees who sew, knit, embroider, and create patterns on clothing while many visitors were also wandering around. During peak hours, in the afternoon, the center was estimated to be jam-packed, and there would be approximately one person per 0.4m^2 of the corridor area. This would mean that the live loads of people would be about 183kg/m^2, which is not constant but is probably the maximum that could be reached. Allowing 4.5kgs per person as the weight of personal belongings, the average live load is approximately 195kg/m^2. This may be compared with the minimum estimated live load of 757kg/m^2 from yield line theory. Therefore, there is a lot of room for live load reduction. Within the shops (3×9m), the occupancy loads of workers, sewing machines, and other items were estimated at 41.5kg/m^2, which is much less than the design live load of 293kg/m^2 recommended by the British standard.

D. Community Marriage Hall

This building was examined on a weekend night during a marriage. People were sitting on the floor, which was covered with a thick carpet. The number of persons sitting on the floor was counted and calculated approximately one per 0.3m^2 of the floor area. This load was too high and probably the maximum that could be accommodated within that space. Therefore, the live load per m^2 of the persons was approximately 210kg/m^2. Adding the additional loads of moveable items, approximately at 24kg/m^2, the total live load becomes 234kg/m^2. This can be compared with the minimum standard estimated live load of 713kg/m^2 based on the yield line theory. It seems that there is also a substantial margin of safety in this case, and therefore, the live load could be reduced to some extent.

E. Primary School Building

This is a standard design adopted by the Education Works Department for the construction of primary schools in various towns and villages of the Sindh province. The original plan consists of only the ground floor with a provision of a first floor when it becomes essential. The classrooms were 5×6m wide, with a central beam that divided the floor slab into two panels of 3×5m. On the floor, the load would be that of children and benches. The benches and the average weight of the children were supposed to be around 32kg. The benches were arranged in two rows, each bench being 2m long. Six children were sitting on each bench. However, 69 students were sitting in the classroom during the investigation. In front, there was a table weighing about 18kg and a chair for the instructor. It was estimated that the weight of each bench was approximately 27kg. Therefore, the total live load on the floor was 2,817kg. The maximum live load using the recommendations of CP-114 was calculated to 1,400kg/m^2, which can be compared with the actual live load of 98kg/m^2. The highest ultimate standard load was 2,918kg/m^2. So again, the margin of safety and, therefore, room for reduction in design live loads is sufficient.

F. Library Building

Libraries are a common feature of cities and an integral part of almost all educational institutions, including high schools, colleges, and universities. This study examined the library building in Moro city. The highest standard ultimate load was 3,270kg/m^2 for CP-110, while the minimum was found for CP-114 and could be taken as a safe load that the slab was capable of carrying without the stresses exceeding their permitted values. The steel almirahs in the library were placed side by side beside the walls, almost touching the ceiling. Books are heavy items and therefore their load is also considerable, but as they are placed beside the wall along the periphery of the room, their load induces a relatively small bending moment. The loads of furniture and persons divided by the floor area were estimated at less than 58kg/m^2. However, considering a specific weight of books at 244kg/m^2 and the total number of books accommodated per panel of the slab, it was found that the uniformly distributed load due to books would be 234kg/m^2. Therefore, the total actual live load was 292kg/m^2.

G. Boys Hostel

The work drawings of the Quaid-e-Awam University College of Engineering, Science & Technology Larkana Hostel and the utilized steel during the construction of the slab were used to calculate the loads. Although the hostel rooms were designed to accommodate three students each, four students were living in each room. There were 4 beds, 4 chairs, and 2 study tables. Assuming 4 visitors and 45kg for each boy's personal belongings, including books, clothes, etc., the total live load on the floor slab would be equal to 980kg. This can be compared with the lowest standard ultimate live load of 2,152kg/m^2 calculated based on CP-114. The difference between actual and standard loads is so high that it can be undoubtedly deduced that the design live loads could have been reduced to decrease the cost of construction. During the games, a large number of students gather in the corridor to watch the match, standing along the periphery. The number of students was estimated to be one per 0.5m^2 of the corridor area. In that case, the live load would be in the range of 122kg/m^2. This is much less than the load-carrying capacity of the slabs and reasonably less than the design live load.

H. Shopping Center

This shopping center is a double-story building in the heart of Larkana city. As the number of visitors seems quite considerable, the live load should not be less than 150kg/m^2 on the corridor, taking into account one person per 0.5m^2 and 2.5kg of personal belongings, and 60kg/m^2 in the shops. Thus, the live load prescribed for such public buildings is almost twice the design imposed. The standard live load carrying capacity of the floor slab was found to be between 483kg/m^2 and 1327kg/m^2.

I. Shopping Mall

This building is located in Hyderabad city. It consists of a basement, a ground floor, and five upper floors. It is a typical example of public buildings with a highly uncertain live load. The loads in stores and corridors were calculated separately, and depending on the heavier items placed in the stores and the extensive mobility of people in the corridors, it was inferred that the loads would not be less than in the previous case of the shopping center. However, as the 2nd, 3rd, and 4th floors were residential apartments, their slabs were reinforced with the same diameter bars and spacing as those of the lower slabs. They were also reinforced with 13mm diameter bars at 150mm c/c with alternate bars bent up. The distribution bars had a 10mm diameter at 200mm c/c. For the residential floors, the margin is quite significant because the calculated live loads are as high as 2,098kg/m^2.

J. University Corridor

This corridor consists of closely spaced columns 2.7m c/c, a relatively smaller width of 3.5m as clear span as compared to the total corridor length of 22m. The corridor was designed for a total load of 975kg/m^2, including the dead load and the live load of 490kg/m^2. The design was accomplished following the elastic theory method. At any given time, it was observed that the number of persons passing never exceeds a single group of 5 or 6 people on a single panel. However, there is the possibility of large groups of students passing through the corridor occasionally. Assuming that the corridor would be jam-packed with an average of one person per 0.4m^2, the live load would be equal to 183kg/m^2, which is only 15% of the ultimate strength of 1,170kg/m^2 given by CP-110. Therefore, there is an enormous scope of reduction.

K. Community Mosque

A multistory mosque was visited on a Friday when most of the people gather to pray. Although many people were sitting closely, people were found sitting sparsely on the first floor. However, it was observed that during prayer, each person requires a strip of 0.5m width and 1.5m length on average, having an area of approximately 0.75m^2. Therefore, the average live load is equal to 102.5kg/m^2. During the sermon, people do not sit in proper rows but gather together randomly, and the load in such a case was estimated at 234kg/m^2, at the rate of one person per 0.3m^2. This is approximately 12% of the maximum ultimate load of 1,908kg/m^2 imposed by CP-110.

L. Public Hospital

The uncertainty on the maximum intensity of live loads and the fluctuation of the occupancy load from point to point and time to time is large. However, in private rooms, the load intensity was not found to be much greater than in standard residential bedrooms. However, in casualty and general wards, the live loads due to visitors and other persons, including staff, other accompanied persons, and those waiting for their turn, are quite high. The maximum standard ultimate load, in this case, was specified as 2,465kg/m^2 by the yield line theory, while the minimum standard ultimate live load was 937kg/m^2 using CP-114. The maximum intensity of the actual load was estimated at 145kg/m^2 for casualties and 39kg/m^2 for private rooms. Therefore, a reduction of the design live load is possible.

TABLE I. ULTIMATE LIVE LOADS FOR THE FLOOR SLABS OF THE STUDIED BUILDINGS

	Case Study	CP-114	CP-110	ACI	Yield line	Assessed load	Code value	Code
		kg/m^2	kg/m^2	kg/m^2	kg/m^2	kg/m^2	kg/m^2	
1	Multistory building	1693	3748	3123	3016	364	147	B
2	Residential villa	1450	1665	1498	1566	22	147	B
3	Vocational training center	864	2157	1581	757	234	390	B
4	Community marriage hall	1161	2435	2415	713	234	488	B
5	Primary school building	1400	2206	2669	2918	98	292	B
6	Library	1742	3270	3050	2723	292	60 reading room 150 stack room 80 corridor	A A A
7	Boys hostel	2152	3428	3953	3621	49	195	B
8	Shopping center	483	1327	1161	1142	210	390	B
9	Shopping mall	1020	2098	1801	1483	151	390	B
10	University corridor	3118	5719	5372	3240	183	390	A
11	Community mosque	844	1908	1630	1327	337	0	B
12	Public hospital	937	2128	1835	2465	185	195	B

III. EXPERIMENTAL STUDY

A square RCC slab panel in a monolithic connection with an edge beam on all four sides with an effective span equal to 600mm and an overall thickness of 50mm was tested by applying a point load at its center. The slab was reinforced with a 3mm diameter wire, as shown in Figure 1.

Fig. 1. The Reinforcement cage.

Fig. 2. Testing arrangement of the model.

Finite element software was used to analyze and design the model, employing a 4-nodded rectangular plate bending element with 3 degrees of freedom at each node. The design flexural load was maintained at 10kN. The punching shear strength of the slab and its ultimate flexural strength based on the actual material properties were determined in the laboratory. Figure 2 shows the testing arrangement of the mode. The calculated live load carrying capacity based on flexure and punching shear was compared with the experimental ultimate load. The behavior of the model was studied in terms of load-displacement history, crack pattern, strain in concrete, mode of failure, and ultimate load [19, 20].

IV. RESULT ANALYSIS AND DISCUSSION

From the case studies and the experimental results obtained, it can be deduced that the live loads adopted for the design of floor slabs are only a small amount of the total load-carrying capacity of the slab, computed based on the strength of concrete, the ratio of reinforcement steel, and boundary conditions. Therefore, there is enough margin to reduce the design live loads and consequently the steel ratio and thus to reduce the cost of materials. However, it was also observed that there are not only live loads but standard requirements for a minimum ratio of reinforcing steel, including distribution steel and partial safety factors, that cause the increase in the moment of resistance of the floor slabs. Thus there is not only the occupancy loads but there are several other aspects as well that must also be studied before concluding, such as creep of concrete, corrosion of steel, temperature stresses, occasional fires, probability of unforeseen drastic overloading, shock loading, lateral loading, redistribution of stresses between concrete and steel and consequently shifting of the neutral axis, quality of workmanship, use of standard materials, human errors during construction, and unexpected behavior of soil beneath the foundation. By examining only the load-carrying capacity and the live loads, it can be asserted that live loads, particularly on residential buildings, could be reduced to the 2/3 of standard values without risking floor overloading. During this investigation, it was observed that in all cases the slabs were designed and reinforcement was provided based on empirical values of bending moment coefficients, enhancing the load-carrying capacity of the slab un-proportionately. More economical sections could be reached if moment fields are predicted with the help of finite element analysis. This explains how the ultimate live loads in all case studies are far higher than the design code value of occupancy loads [20].

V. SUGGESTIONS

The scope of this study could be extended to a broader range of public buildings in metropolitan cities, such as Karachi and Lahore in Pakistan or any other part of the world. A systematic investigation should be carried out on the floor areas where heavy concentrated loads of equipment and machinery are expected. It is also imperative to investigate the matter more objectively and study the long-term effects on the stability and durability of buildings if the reinforcement is reduced based on reduced design live loads. Furthermore, no matter how rare, there is always a possibility of strong wind currents during a storm, which might cause over-stressing of the slab, which would then act as coupling media to resist the overturning effect of the lateral wind forces. This is where the additional moment of resistance due to higher design live loads would provide an extra margin of safety against failure. Other sources of uncertainty, such as steel corrosion, concrete cover splitting, temperature stresses due to occasional exposure to fire, unexpected behavior of the soil beneath the foundation, and human errors during construction, should also be investigated.

VI. CONCLUSION

The presented case studies showed that there is sufficient margin to reduce the design live loads on the floor slabs of residential buildings, particularly in multistory apartment blocks, reducing their construction cost. By considering the load-carrying capacity and occupancy loads, it can be affirmed that live loads, especially on residential buildings, could be decreased to two-thirds of the code values without risking floor overloading. Experimentally, the actual strength of the RCC slabs was several times higher than the design loads and the ultimate loads proposed by the standards. Therefore, there is enough margin to reduce construction cost by reducing the amount of reinforcement, providing that serviceability limits and code provisions regarding minimum reinforcing and distribution steel are not disregarded.

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