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ANALYSIS OF THE IMPACT OF DAMAGE TO REINFORCED CONCRETE BEAMS ON STRENGTH AND DEFORMABILITY

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Buildings often require inspection or reconstruction of reinforced concrete elements due to new regulations, technical equipment and changes in operating conditions. During reconstruction, there is a need for through openings to lay utilities and install modern engineering systems. Studies show that such openings generally reduce the strength of reinforced concrete elements. The impact of openings depends on their location, size and shape: openings in the support areas and compression zones have the most negative impact on strength, while openings in the middle of the span or neutral axis are less harmful. Round openings have a smaller effect on stresses than square openings. However, there is still insufficient research on the impact of such openings on structures in service, which requires additional research to formulate clear recommendations and ensure the reliability of buildings in the long term.

Key words: web-opening, reinforced concrete beam, through damage, shear strength, bearing capacity, damage under operating load, strength and deformation properties.

Introduction

In Ukraine, most of the buildings and structures were built before 1970, which is almost 65.6 % of the total building stock of Ukraine. Therefore, it can be assumed that most of these buildings may not comply with the new engineering system design codes. It follows that it is necessary to carry out a qualitative assessment of these buildings and structures and determine their residual safety margins in accordance with their condition. A special role in the reconstruction will be played by the installation of new engineering systems or networks in accordance with the current standards and regulations. Thus, an important part of the reconstruction of buildings will be the determination of the bearing capacity of reinforced concrete elements under the influence of operational load with the arrangement of opening in their body for the passage of communications.

The purpose of this study is to analyze scientific sources and various scientific developments that contain information or description of the impact of web-openings and various types of damage in reinforced concrete elements and their impact on the strength-strain state of those element, its crack resistance and residual bearing capacity. Finding regularities and identifying the principles of damage impact on structures, as well as establishing insufficiently researched or unexplored aspects in this area is the other main focus of this study.

Materials and methods of research

To lay utility networks in reinforced concrete elements, there is a need to create openings of various sizes, geometries, and locations. Based on researches, three main characteristics were identified: the geometry of the opening, its location and quantity.

According to research by scientists from around the world, the openings can be round, square or rectangular. In his scientific work (Saeed Ahmed Al-Sheikh, 2014) investigated the residual bearing capacity of reinforced concrete beams with different openings shapes. Researchers discovered that the round ones

causes the smallest reduction in the ultimate load. The rectangular openings, compared to the square one, increased the residual bearing capacity by 4 %, while the round opening reduced it by 8 % relative to the square one.

In the research of (Chin, S.C. & Shu Ing, Doh., 2014) compared round and square openings in terms of deflection under load and crack structure. The results showed that round openings can reduce the bearing capacity of a beam by 30–35 % of the original value, while square openings lead to a more significant reduction in strength, approximately 40-80 % compared to intact beams without damage.

According to the research of (Alsaeq & Haider M. 2013), the best opening shape is a narrow rectangular hole with long sides extended horizontally. Such an opening provided the highest bearing capacity, in the range of 65–60 kN, depending on its location in the beam, compared to a rectangular opening extended vertically and square ones, which showed results in the range of 65–120 kN. However, in some practical cases, this shape may not be suitable. The round opening has an advantage over the square one in terms of structural strength of the beam.

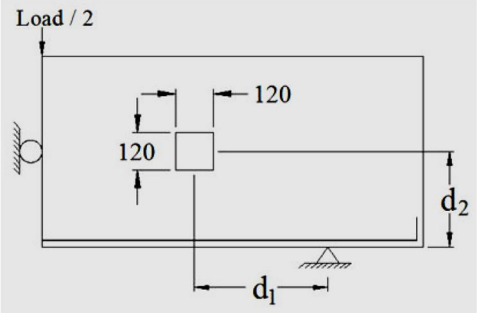

Fig. 1. Rectangular opening in the body of the beam (Alsaeq & Haider M. 2013)

The size of the opening has a critical effect on the bearing capacity of reinforced concrete beams on the shear strength. Studies conducted by (Nguyen Trung & et al.; 2023) and (Saeed Ahmed Al-Sheikh, 2014) showed that with large openings, the bearing capacity decreases by 64 % and the deflection increases by 57 %. With smaller openings, the bearing capacity decreases by only 10 % and the deflection increases by 11 % compared to the control sample.

The team of researchers (Sathiyapriya, D. & et al., 2021) studied the behavior and crack formation at different opening diameters and concluded that at opening diameters smaller than 0.3 of the beam height, the behavior of the beam is almost the same as that of beams without web-opening. However, it is important to consider the location of the web-opening and the minimum depth of the compression chord. If the diameter of an opening exceeds 0.3 times the height of the beam section, the increase in load leads to the formation of cracks around an opening, which significantly reduces the bearing capacity of the beams.

Researches (Javad Vaseghi Amiri & Morteza Hosseinalibygie., 2004) came to similar conclusions that the appearance of the first cracks in beams with openings does not depend on the presence of the opening and occurs at a load of approximately 3–4 tons for all beams with normal or high-quality concrete. However, shear cracks around the hole appear earlier than in solid beams, and the load at which shear cracks appear in beams with normal concrete decreases with increasing hole diameter. However, the shape and nature of the cracks depend on the diameter of the opening. If the diameter of the hole exceeds 1/3 of the depth of the beam, its behavior and type of failure change. Increasing the concrete strength does not have a significant impact on crack control if the hole diameter is less than 1/3 of the depth.

The study also proved that the size of the vertical circular opening has a significant impact on the maximum deflection, increasing it by 1–2 mm and reducing the bearing capacity of the beam by up to 30 %. In addition, it was found that the effect of the openings size is more significant than the effect of the number of web-openings: two vertical openings with a diameter of 100 mm affect the structure by 5–7 % less than one vertical ones with a diameter of 150 mm (Sayed Ahmed., 2019).

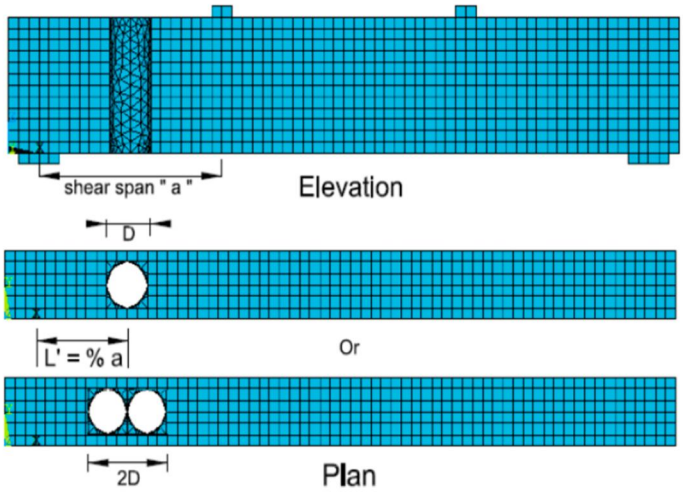

Fig. 2. location of the vertical opening in the beam body (Sayed Ahmed., 2019)

The most critical location for an opening in beams designed and manufactured from normal concrete is the area near the support. This is because in these areas, the cross-section of the beam is insufficient to absorb significant shear forces, which can lead to a reduction in load carrying capacity of more than 20 %. The best place for the opening is the middle of the distance between the point of load application and the beam support (the middle of the shear span), which reduces the bearing capacity by only 12.5 % (Javad Vaseghi Amiri & Morteza Hosseinalibygie., 2004).

In the work, (Saeed Ahmed Al-Sheikh, 2014) came to similar conclusions: the location of an opening in the shear zone leads to a sudden decrease in the ultimate load by about 38 %. If the opening is located near the supports, the reduction is about 18 %. In the bending zone, this effect is less pronounced, with a decrease of about 6 %.

Increasing the diameter of an opening in beams made of ordinary concrete changes the structure of crack propagation and the type of failure. Initially, cracks appear perpendicular to the span of the beam in the tensile zone, but with an increase in the opening, their propagation switches to the shear type, where cracks form at an angle to the horizontal faces of the beam (Javad Vaseghi Amiri & Morteza Hosseinalibygie., 2004).

Studies have shown that specimens with openings in the tensile zone are slightly affected, with a 7 % to 14 % reduction in tensile strength. The beams were able to recover up to 46 % of the lost strength due to carbon fiber reinforcement (Fu Li & et al., 2023). Consequently, drilling openings in the shear zone are not recommended, as the loss of strength can reach 57 %, even with strengthening. Shear cracks can occur in the corners of the openings, even in the tensile zone. After reinforcement with FRP sheets, a decrease in crack density is observed, which reduces the stress in the concrete.

The openings can not only reduce the stress-strain characteristics, but also increase them. In the works of (Fu Li & et al., 2023; & Yamada & Yuta., 2019), an innovative design of small through transverse holes was proposed to enhance the bearing capacity of inclined cross-sections of reinforced concrete beams. The results of experiments and numerical calculations showed that this arrangement of transverse openings can improve the strength of inclined sections and the deformation capacity of beams compared to reference samples.

According to the studies of Chinese researchers (Yamada & Yuta., 2019) and a Japanese researcher (Fu Li & et al., 2023), beam shear strength can be strengthened by using small openings properly located in the zone of diagonal crack formation. This arrangement helps redistribute stresses and change the formation of cracks, which leads to a 32 % increase in shear strength and a 97 % improvement in deformability of the beams compared to the control beams.

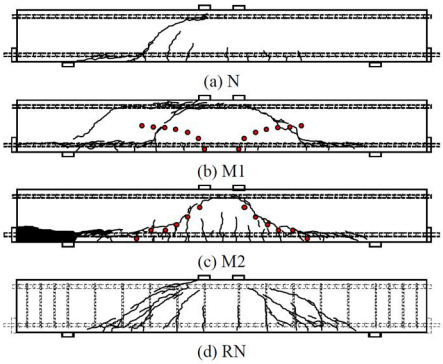

Fig. 3. Diagram of the location of small holes in the zone of inclined crack formation (Yamada & Yuta., 2019)

The analysis also showed that in beams with openings located from the points of load application to the location of the stretched reinforcement in the middle of the span, when a horizontal crack occurred, the strength increased to the flexural strength. However, if there were vertical cracks in the beam, the strength decreased by up to 80 % relative to the reference beams. At the same time, for beams with openings located from the bottom of the load points to the middle of the height without clamps, the strength increased by 110–160 % compared to beams without openings, regardless of the location of the cracks. The load-bearing capacity of the inclined cross-sections did not change if the crack width exceeded 0.3 mm, and the changes in the behavior of the beams with clamps were insignificant, regardless of the location of the openings. It was found that these changes were caused by the contribution of arch mechanisms, enhanced by the localization and expansion of the minimum principal stress distributions due to the presence of multiple openings.

Results and discussion

Having studied a significant body of scientific work on this topic, it can be argued that pre-sealed openings significantly affect the strength and deformation characteristics of reinforced concrete elements, significantly reducing their residual bearing capacity. This issue is of great importance, as a decrease in the strength of elements can lead to critical consequences in the construction and operation of buildings and structures. The most negative effect on the strength characteristics of reinforced concrete elements is observed when openings are located in the supporting areas or in the compressed zone of the elements, reducing the bearing capacity by 8–23 %, depending on the shape of the opening. This is because the maximum stress is concentrated in these areas, and the presence of openings significantly changes the stress distribution, reducing the ability of the elements to withstand the load. Accordingly, openings located in the middle of the span, especially in the stretched or neutral zone, have the least negative impact on the bearing capacity of the elements, since in these zones the stresses are lower and the impact of the openings is not so critical. The geometry of the openings also plays an important role in influencing the strength-strain characteristics. The stress redistribution that occurs around the holes depends on the shape of the opening. Round holes have a lesser impact, reducing the bearing capacity by 1–8 %, as they contribute to a more even distribution of stresses around them. Square holes, on the other hand, lead to a concentration of stresses in the corners, which reduces the bearing capacity by 8–19 %. In addition, the size of the openings is also crucial. They can be classified into small openings, which are up to 1/3 of the height of the beam section, and large openings, which exceed 1/3 of the height of the beam section. Small openings have a smaller impact on the strength characteristics, and beams with such openings usually behave similarly to beams without holes until the first cracks appear. However, after the cracks appear, the load-bearing capacity of such beams decreases sharply compared to control beams without holes. Large holes significantly reduce the strength of reinforced concrete elements from the very beginning. It is important to note that the vast majority of scientific studies do not consider the issue of holes in existing structures that are already in operation. This creates a certain problem, since the conclusions regarding the impact of openings on the structures in service cannot be directly applied to real conditions and require further, more in-depth research. Such studies should include analysis of the behavior of structures under the influence of operational load, determination of the residual strength of elements after the installation of holes and development of recommendations for the safe performance of such works without a critical reduction in the bearing capacity of reinforced concrete elements.

Conclusion

1. Classification of web-openings: one can be classified into large (more than 1/3 of the beam section height) and small (less than 1/3). Beams with small openings exhibit similar strength-strain behavior as intact beams until the first cracks appear.

2. The geometry of the openings has a significant impact on the load-bearing capacity. Round ones are the best option, as they reduce the bearing capacity of reinforced concrete elements by 1–8 %. Square (8–19 %) and rectangular (8–23 %) openings have a greater negative impact due to the concentration of stresses in the corners.

3. Location of web-opening: The placement of the opening in the beam also plays an important role. Rectangular openings are best placed in the center of the span on the neutral axis. The diameter of round ones affects the strength characteristics more than the number of openings.

4. Potential reinforcement: In addition to reducing the strength, properly placed small diameter openings can reinforce reinforced concrete elements. In particular, openings in the tensile areas of the span during the monolithic works can increase the bearing capacity of inclined cross-sections by up to 32 %.

Prospects for further research

More detailed and in-depth research in this area is extremely important and will have significant practical value for projects to reconstruct or strengthen reinforced concrete elements. Such research will allow the development of new recommendations and techniques to help engineers and architects work effectively and safely with existing structures. This, in turn, will expand the possibilities for laying new networks and communications in already constructed buildings, which is an urgent task in modern construction and reconstruction. Thanks to such research, engineers will have more tools to assess the condition of reinforced concrete structures after openings or other damage, which will minimize risks and ensure the durability of structures. Architects, in turn, will be able to take a more flexible approach to designing reconstructions, knowing what technical limitations and opportunities exist when working with reinforced concrete elements already in use. Thus, conducting additional research in this area is not only scientifically important but also practically necessary to ensure safety and efficiency in the reconstruction and modernization of buildings and structures, especially those that have been in use for a long time. This will open up new perspectives in the use of modern building materials and technologies, as well as contribute to the development of new standards and norms that take into account the specifics of working with existing reinforced concrete structures.

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АНАЛІЗ ВПЛИВУ ОТВОРІВ ТА ПОШКОДЖЕНЬ ЗАЛІЗОБЕТОННИХ БАЛОК НА МІЦНІСТЬ ТА ДЕФОРМАТИВНІСТЬ

Багато будівель та споруд під час експлуатації потребують обстеження, реконструкції або підсилення залізобетонних елементів. Це пов'язано з появою нових норм і рекомендацій, розробленням нового обладнання, для якого необхідно прокладати інженерні мережі, а також зі змінами умов та тривалості експлуатації конструкцій та інженерного обладнання. Під час реконструкції будівель часто виникає потреба у виконанні наскрізних отворів або пошкоджень у залізобетонних елементах для прокладання нових комунікацій і систем. Наукові дослідження цього питання розглядають вплив таких отворів на міцнісно-деформаційні характеристики залізобетонних елементів. Основні аспекти, що впливають на ці характеристики, охоплюють розташування отворів у тілі елемента, їх геометрію, форму та розмір. Загалом, науковці дійшли висновку, що отвори знижують міцнісні характеристики залізобетонних елементів порівняно з еталонними зразками без отворів. Проте є дослідження, які показують, що отвори в зонах похилих перерізів можуть покращити деформаційні показники. Більшість досліджень не описує поведінку залізобетонних елементів з наскрізними пошкодженнями під час експлуатації, а також не надає рекомендацій щодо їх розташування та впливу на залишкову несучу здатність. Результатом аналізу наукових статей та досліджень різних науковців є такі висновки: дослідження показують, що попередньо закладені отвори в залізобетонних елементах знижують їхню залишкову несучу здатність. Найнегативніше впливають отвори в опорних ділянках та стиснутій зоні, тоді як отвори в середині прольоту, в розтягнутій або нейтральній осі, впливають менше. Геометрія отворів також впливає: круглі отвори спричиняють найменший вплив на перерозподіл напружень, тоді як квадратні – найбільший. Отвори можна поділити на малі (до 1/3 висоти балки) та великі (понад 1/3). Більшість досліджень не охоплює вплив отворів на експлуатовані конструкції, що потребує додаткових досліджень.

Ключові слова: залізобетонна балка, наскрізні пошкодження, похилі перерізи, несуча здатність, пошкодження при дії експлуатаційного навантаження, міцнісно-деформаційні властивості.