Збірник наукових праць. Галузеве машинобудування, будівництво
Academic journal. Industrial Machine Building, Civil Engineering
http://journals.nupp.edu.ua/znp
https://doi.org/10.26906/znp.2025.65.4202

UDC 624.016

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# Numerical studies of the resistance of concrete keyed joints with rectangular keys in reinforced concrete structures

Abstract. Numerical investigations were carried out on the behavior of keyed joints with rectangular keys in reinforced concrete elements under different failure mechanisms. A two-dimensional nonlinear model was developed in Simulia Abaqus with the concrete damage plasticity approach, accounting for material nonlinearity and contact interaction between joint components. Various failure modes were received, including through-crack formation, key tearing-off, shear failure, and bearing surface crushing. It was investigated how the tensile and compressive strength parameters of concrete affect the bearing capacity of a concrete joint under different types of failure. The specifics of modeling such problems in Simulia Abaqus and the problems of solution convergence were studied.

Keywords: bearing capacity, reinforced concrete keys, deformation model, numerical simulation.

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Received: 11.10.2025 Accepted: 18.11.2025 Published: 26.12.2025

**Introduction.**

Keyed joints of reinforced concrete elements are used in various structural systems to ensure the composite action of slabs, beams, columns, shear walls, etc. Despite the uniform principle of load transfer through the keyed joint, its configuration may vary significantly, leading to different failure modes.

The stress state of keyed joint material is characterized by a complex stress distribution pattern due to the specific geometry of the key, particular boundary conditions, nonlinear behavior of concrete in the pre-failure stage, and nonlinearity of contact conditions. Consequently, such joints are difficult to analyze using analytical methods or require significant simplifications of the failure mechanism, which necessitates validation through experimental testing.

An alternative approach to studying the bearing capacity of keyed joints is the use of the finite element method, which allows obtaining a detailed stress and strain distribution pattern while accounting for the geometric parameters of the joint, nonlinear material behavior, and contact interaction features with the connected elements.

Failure of keyed joints can occur according to different mechanisms [1] depending on geometric parameters, confinement, and reinforcement. Different failure modes require different methods for determining the ultimate load capacity of the joint. The accuracy of such methods is often limited by significant simplifications – for example, assumptions of uniform stress distribution or predetermined failure surface geometry [2]. However, the conditions of composite action between the joint concrete and connected elements, presence of cracks, and stress concentrations considerably complicate the analytical description of the stress-strain state.

At the same time, relatively few studies have addressed the computer modeling of keyed joints in reinforced concrete elements. Among these are works [3-7] that investigate the stress-strain state of keys, their load-bearing capacity, and provide comparisons with experimental test results.

**Problem statement.**

This study aims to analyze the stress-strain state and load-bearing capacity of reinforced concrete keyed joints, accounting for their geometry, concrete deformation properties, and load transfer mechanisms between joint components. This will allow for investigating the conditions leading to various failure modes and optimizing the design solutions for such structural elements.

**Main material and results.**

Keyed joints in reinforced concrete elements exhibit several possible failure modes, the main ones being: joint failure with crack formation between opposite key corners, tearing-off failure, key shear, and crushing under bearing surfaces (Fig. 1).

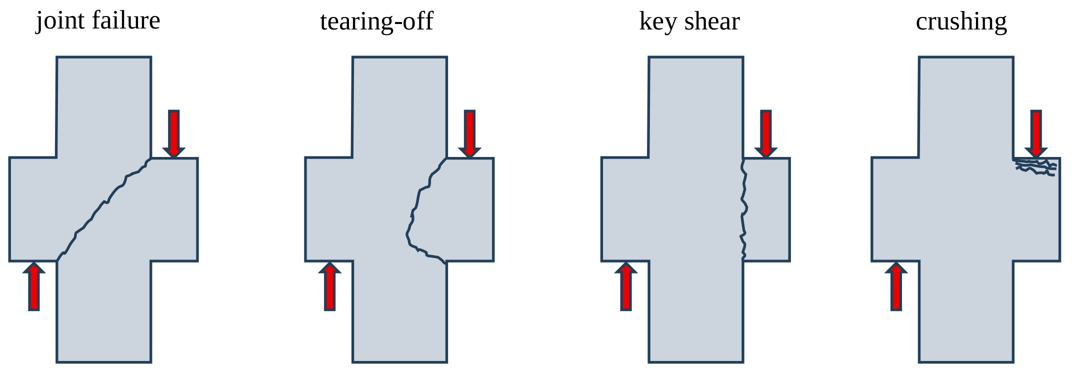


**Figure 1 – Failure modes of keyed joints**

This study investigates the behavior of a keyed joint with a single rectangular key using the Simulia Abaqus software, which enables modeling of nonlinear problems, including material nonlinearity, tensile behavior of concrete, and contact surface interactions.

Simulia Abaqus provides the capability to model the stress-strain behavior of reinforced concrete structures through the smeared crack concrete model, brittle crack model, and concrete damage plasticity (CDP) model. In this study, the latter was chosen as it provides the most comprehensive description of concrete behavior under tension and compression, including static and cyclic loading.

The general model parameters were adopted according to the recommendations in [8], specifically: dilation angle of 36°, eccentricity of 0.1, viscosity parameter of $10^{-5}$, and ratio of biaxial to uniaxial compressive strength of 1.16. The stress-strain relationships in compression and tension were adopted according to Eurocode [9] recommendations, accounting for nonlinearity and the descending branch of the diagram.

Considering the interaction features of keyed joint elements in building structures, where the stress state of the joint material approaches plane stress conditions, a two-dimensional analysis was adopted, which significantly simplifies modeling and result interpretation.

The key concrete typically has lower properties compared to the concrete of the connected elements; therefore, failure is expected to occur in the key material. Nevertheless, it is advisable to include in the finite element model a portion of the connected element material that interacts with the key material, as the stiffness of these elements can affect the overall stress-strain state of the joint.

The interaction between the key surfaces and the connected elements was modeled in both normal (hard contact) and tangential (with a friction coefficient of 0.7) directions, which ensures realistic representation of contact surface interaction. Contact settings were configured to allow free separation, thus excluding the possibility of tensile stress between contact surfaces.

The model employed plane finite elements of type CPS3. A preliminary mesh sensitivity analysis was conducted, confirming result convergence with a mesh density of 8-10 finite elements per unit length of the characteristic dimension. The analysis was performed using Dynamic Explicit solver with geometric nonlinearity enabled and automatic time stepping.

The model dimensions and boundary conditions are shown in Fig. 2. The dimensions were selected to match those from experimental studies [1]. Boundary conditions were defined exclusively as kinematic constraints, including at the loading area where load was applied through controlled displacement. This allows more accurate capture of the peak load and obtaining the complete load-displacement curve including the softening branch.

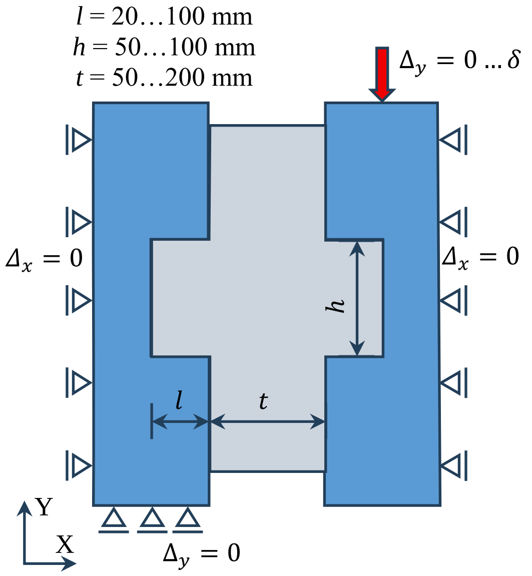


**Figure 2 – Model geometry and boundary conditions**

The baseline properties of the key concrete were adopted from experimental fiber-reinforced concrete specimens [1], specifically:

– compressive strength $f_c = 12 MPa$;

– tensile strength $f_{ct} = 1.48MPa$, which is close to the Eurocode [9] recommended value of $f_{ct} = 0.3 * f_c^{0.667} = 1.57MPa$;

– the fracture energy $G_f$ was varied over a wide range, as different sources provide different recommendations for this parameter. The most used is the empirical formula $G_f = 73f_c^{0.18}$, recommended in [10]. Earlier CEB-FIP 1993 recommendations [11] provide the relationship $G_f = (25 \dots 58) * (0.1f_c)^{0.7}$ depending on aggregate size. Moreover, the values obtained from these relationships differ by more than a factor of two. It should be noted that for fiber-reinforced concrete, this parameter can be significantly higher due to the relatively high tensile deformability of fibers during crack formation, since the fracture energy Gf generally depends on both the tensile strength and deformability of concrete (i.e., the length of the concrete tensile stress-strain curve).

As preliminary results showed, with baseline model settings the load-displacement curve exhibits oscillations in most cases (Fig. 3), which can be overcome by artificially adding viscosity parameters to the model. However, the linear and quadratic viscosity coefficients of 0.06 and 1.2, respectively, recommended in many studies [9,13,14,15], do not resolve the oscillation problem (Fig. 3a). Smooth load-displacement curves (Fig. 3b) were achieved only by increasing these coefficients by a factor of 10…20. This also significantly affects the peak load value.

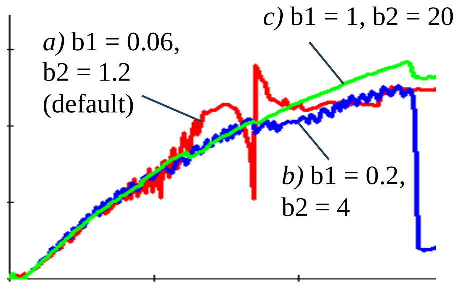


**Figure 3 – Load-displacement curves for different viscosity parameter settings**

In addition to the factors mentioned above, friction between the contact surfaces of the key and the connected elements can play an important role in the behavior of a keyed joint. Accounting for friction makes it possible to more accurately reproduce the actual performance of the joint, affects the shape of the load–displacement curve, and can significantly change (usually reduce) the convergence of the numerical analysis. The presence of friction forces partially redistributes the load, slows down deformation, and increases the load-carrying capacity of the structure. These effects arise due to the transfer of tangential forces both on the “working” faces and on the side faces of the key. This is especially pronounced at the initial stages of loading, when the contact surfaces have not yet undergone significant plastic strains and retain a relatively high coefficient of friction.

In order to quantitatively analyze the influence of surface friction forces on the load-carrying capacity of the structure, numerical simulations of the key resistance were performed with friction taken into account using the Coulomb friction model, in which the friction force is proportional to the normal contact force. In the study, calculations were carried out for various values of the coefficient of friction in the range from 0 to 1. The results showed a significant influence (up to 226%) of this parameter both on the deformation curve and on the maximum load value (Fig. 4).

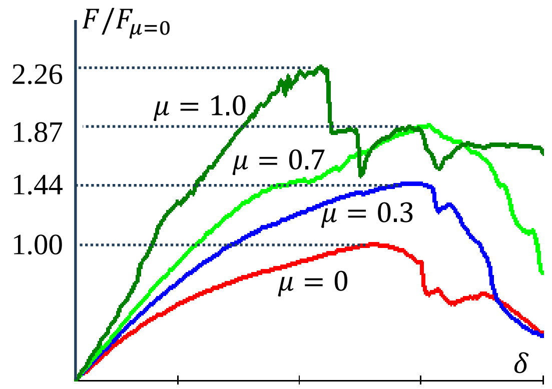


**Figure 4 – Load-displacement curves for different friction ratio**

In addition to friction, the work of a keyed joint can also be affected by adhesion between the contact surfaces of concrete, which is due to the adhesion of cement stone, micro-engagement of irregularities and the presence of chemical and physical bonds in the surface layer. Adhesion forces appear mainly at the initial stages of loading and contribute to the transmission of tangential forces even in the absence of noticeable normal pressure, increasing the initial stiffness of the joint. With increasing load and the development of microcracks, the adhesive bond gradually collapses, and the further work of the contact is determined mainly by friction and crushing of concrete. In these numerical simulations, the effect of adhesion was not taken into account, however, in subsequent studies it is advisable to consider adhesion as an additional factor that can affect the bearing capacity of a keyed joint.

Investigation of concrete joint behavior for different dimensions indicates various possible failure modes. The failure pattern is optimally assessed through visual analysis of tensile plastic strain distribution at highly magnified displacements. Different failure modes are shown in Fig. 5.

The first failure mode is characterized by tensile plastic strain development between opposite key corners, which exceeds strains in other parts by several times (Fig. 5a). Different sizes of the joint width and the height of the key give different values of the length of such a crack and its angle of inclination. But in many tested cases this crack always remained close to rectilinear and was located between the opposite corners of the keys. As the load increases, plastic strains begin to develop from the corners of the keys and spread into the body of the joint.

In key tearing-off failure (Fig. 5b), similar plastic strains develop but do not extend across the entire joint body, instead localizing near the key. This failure type occurs at higher key length-to-height ratios.

When the bearing surface area is insufficient, crushing occurs, accompanied by high stresses due to inadequate load transfer area (Fig. 5c).

Key shear failure (Fig. 5d) occurs when the key cross-sectional area is insufficient while the key length is relatively small. In this case, plastic strains of concrete does not propagate into the joint interior but remains concentrated at the key-joint interface cross-section. As the load increases, plastic strains develop from the load corner of the keys to another corner almost along a straight trajectory.

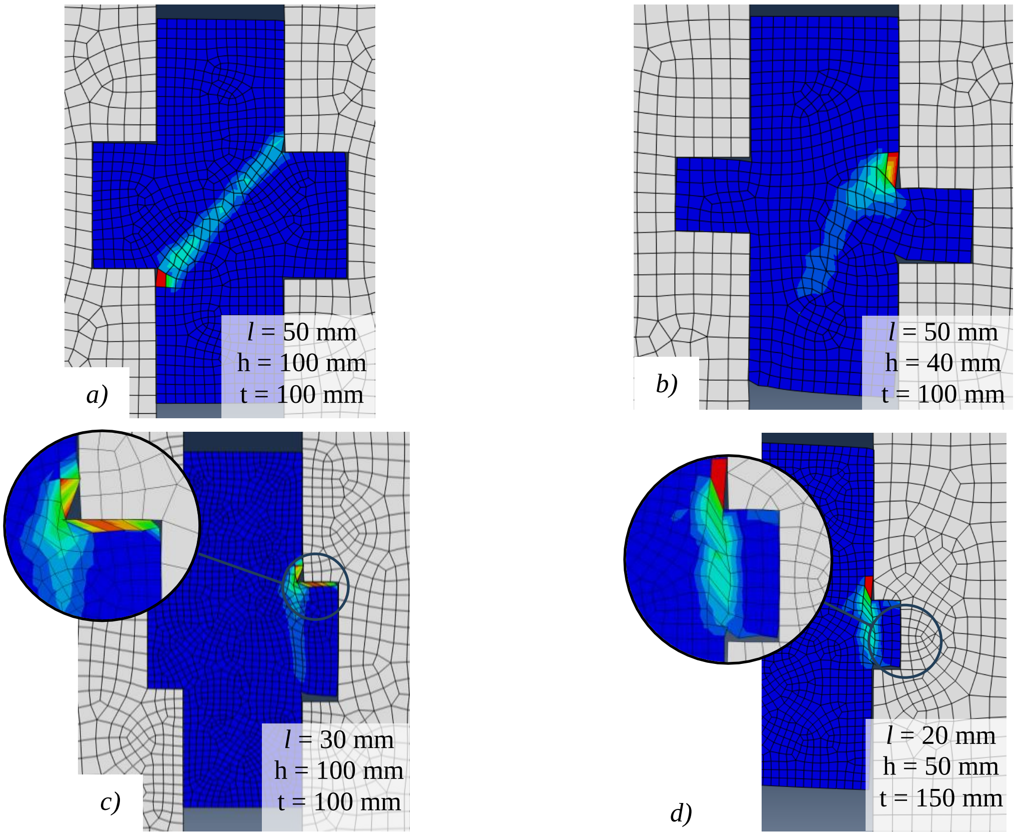


**Figure 5 – Failure modes of keyed joints:**
**(a) crack formation between opposite key corners; (b) key tearing-off;**
**(c) key surface crushing; (d) key shear**

Fundamentally different failure mechanisms use concrete mechanical properties differently. It is evident that bearing surface crushing is governed by concrete compressive strength, while for the other failure modes tensile strength is the more critical parameter.

For instance, when concrete compressive strength $f_c$ is increased by 50% (with all other parameters unchanged), the joint load-bearing capacity increases by only 3% for through-crack failure, by 7% for tearing-off and shear, but by 30% for crushing. Thus, increasing the concrete grade, which primarily raises compressive strength, is effective mainly for cases where bearing surface crushing is more likely.

Increasing concrete tensile strength (with strain values unchanged) leads to proportional increase in fracture energy, so these parameters were varied simultaneously in the study. Their 50% increase resulted in 35-40% higher load-bearing capacity for different joint widths in the case of joint failure (Fig. 5a). However, for key tearing-off failure (Fig. 5b), the corresponding increase was only 13%.

Concretes with crack-resistance enhancing inclusions (fiber-reinforced concretes) have significantly higher fracture energy due to increased ultimate strains, although this may not be accompanied by substantial tensile strength increase. Therefore, a more detailed investigation of fracture energy $G_f$ influence within the range of 40-120 J/m² was conducted, showing 20-25% load-bearing capacity increase only for joint failure and only when $G_f$ increased from 40 to 60 J/m². Further increase of this parameter to 120 J/m² did not result in significant capacity changes but only extended the deformation zone at peak load.

**Conclusions.**

Numerical investigations have shown that, depending on the joint failure mechanism, concrete tensile and compressive strengths affect the load-bearing capacity of reinforced concrete joints differently. Different key geometric parameters govern different failure modes. The results emphasize the necessity of detailed consideration of concrete properties and convergence control for reliable modeling of keyed joint resistance in reinforced concrete elements.

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# Чисельні дослідження опору бетонних шпонкових з'єднань з прямокутними шпонками у залізобетонних конструкціях

Аннотація. Актуальним питання розрахунку елементів будівельних конструкцій залишається визначення несучої здатності з'єднань, у тому числі. бетонних шпонкових з'єднань у залізобетонних конструкціях. Незважаючи на єдиний принцип передачі навантаження через бетонне шпонкове з'єднання, його конфігурація може суттєво відрізнятися, що приводить до різних форм руйнування.
Напружений стан матеріалу шпонкових з'єднань характеризується складною картиною розподілу напружень через особливості форми шпонки, особливості крайових умов, нелінійну роботу бетону в передруйнівній стадії та нелінійність умов контакту. Зважаючи на це, такі з'єднання слабо піддаються аналітичним методам досліджень або ж потребують значних спрощень схеми руйнування, що потребує верифікації експериментальними випробуваннями.
Альтернативним варіантом дослідження міцності шпонкового з'єднання є використання методу скінченних елементів, який дає змогу отримати детальну картину розподілу напружень і деформацій.
У статті досліджується опір шпонкових з'єднань із урахуванням геометричних параметрів стику, нелінійної роботи матеріалу шпонки, особливостей контактної взаємодії із елементами, що з'єднуються, тощо. Використано чисельне моделювання в ABAQUS із застосуванням моделі бетону CDP для прогнозування механізмів руйнування. Результати моделювання показують значний вплив на несучу здатність геометричних параметрів стику а також параметрів міцності бетону як на стиск так і на розтяг, особливостей контактної взаємодії із елементами, що з'єднуються.

Ключові слова: несуча здатність, залізобетонні шпонки, деформаційна модель, числове моделювання.

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| Надіслано до редакції: | 11.10.2025 | Прийнято до друку після рецензування: | 18.11.2025 | Опубліковано (оприлюднено): | 26.12.2025 |
|---|---|---|---|---|---|

Suggested Citation:

| APA style | Demchenko, O., & Myshchenko, M. (2025). Numerical studies of the resistance of concrete keyed joints with rectangular keys in reinforced concrete structures. *Academic Journal Industrial Machine Building Civil Engineering*, *2*(65), 46-51. https://doi.org/10.26906/znp.2025.65.4202 |
|---|---|
| DSTU style | Demchenko O., Myshchenko M. Numerical studies of the resistance of concrete keyed joints with rectangular keys in reinforced concrete structures. *Academic journal. Industrial Machine Building, Civil Engineering*. 2025. Vol. 65, iss. 2. P. 46–51. URL: https://doi.org/10.26906/znp.2025.65.4202. |