International Journal for Computational Civil and Structural Engineering, 20(4) 57–71 (2024)

DOI:10.22337/2587-9618-2024-20-4-57-71

ENHANCING THE DAMPING BEHAVIOUR OF STEEL CRANE STRUCTURES BY INTRODUCING A CONCRETE CORE

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Abstract: The potential use of steel tube confined concrete columns in crane structures is being explored as a means of enhancing damping during the movement of carrying and lifting machines. This is with a view to mitigating the impact of dynamic effects that may arise during operation. The results of experimental studies of tube confined concrete specimens for stability under central compression by static loading are given. This paper presents a methodology for dynamic tests of specimens, which is used to determine the damping ratio of vibrations and the inelastic resistance coefficient of composite materials. The results demonstrate that tube confined concrete specimens possess enhanced damping behaviour in comparison to steel and reinforced concrete structures. This observation suggests that they are an effective solution for load-bearing structures designed to support moving overhead cranes.

Keywords: crane structures, steel tube confined concrete, critical load, natural vibration frequency, damping ratio, inelastic resistance coefficient, damping

УЛУЧШЕНИЕ ДЕМПФИРУЮЩИХ ХАРАКТЕРИСТИК СТАЛЬНЫХ ПОДКРАНОВЫХ КОНСТРУКЦИЙ ПОСРЕДСТВОМ ИНТЕГРАЦИИ БЕТОННОГО СЕРДЕЧНИКА

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Аннотация: Изучается перспектива применения трубобетонных колонн в подкрановых конструкциях с целью увеличения демпфирования во время движения подъемно-транспортных машин, подверженных динамическим воздействиям в процессе эксплуатации. Представлены результаты экспериментальных испытаний трубобетонных образцов на устойчивость под действием центрального сжатия статической нагрузки. Описана методика динамических испытаний образцов, на основе которой определены коэффициенты демпфирования колебаний и неупругого сопротивления. Полученные результаты показывают, что трубобетонные образцы обладают более высокими демпфирующими свойствами, чем стальные и железобетонные, что свидетельствует об их эффективности в качестве несущих конструкций, предназначенных для мостовых кранов.

Ключевые слова: подкрановые конструкции, трубобетон, критическая нагрузка, частота собственных колебаний, декремент затухания, коэффициент неупругого сопротивления, демпфирование

1. INTRODUCTION

Crane structures are an integral component of modern industrial plants, serving a crucial function in ensuring the safety and operational efficiency of these facilities. Fig. 1 illustrates the configuration of load-bearing and crane structures, with arrows indicating the potential movements of the crane trolley 1 along the overhead crane 2 and the girder itself along the crane rails 3 on crane girders 4. The columns 5 in crane systems may have various cross sections, including open sections such as I-beams or channels, as well as closed sections having rectangular, square and circular cross sections.

In the design of crane structures, it is essential to consider both static and dynamic loads in order to create a structure that can withstand the full range of forces acting on the crane during its operational lifetime. During operation, a number of factors can contribute to vibrations in crane structures. These include uneven load lifting, sudden changes in crane speed, wind effects, malfunctions in the control system, wear and tear of materials, and geometric imperfections in the structure. Additionally, vibration effects from surrounding machines can also play a role [1-3].

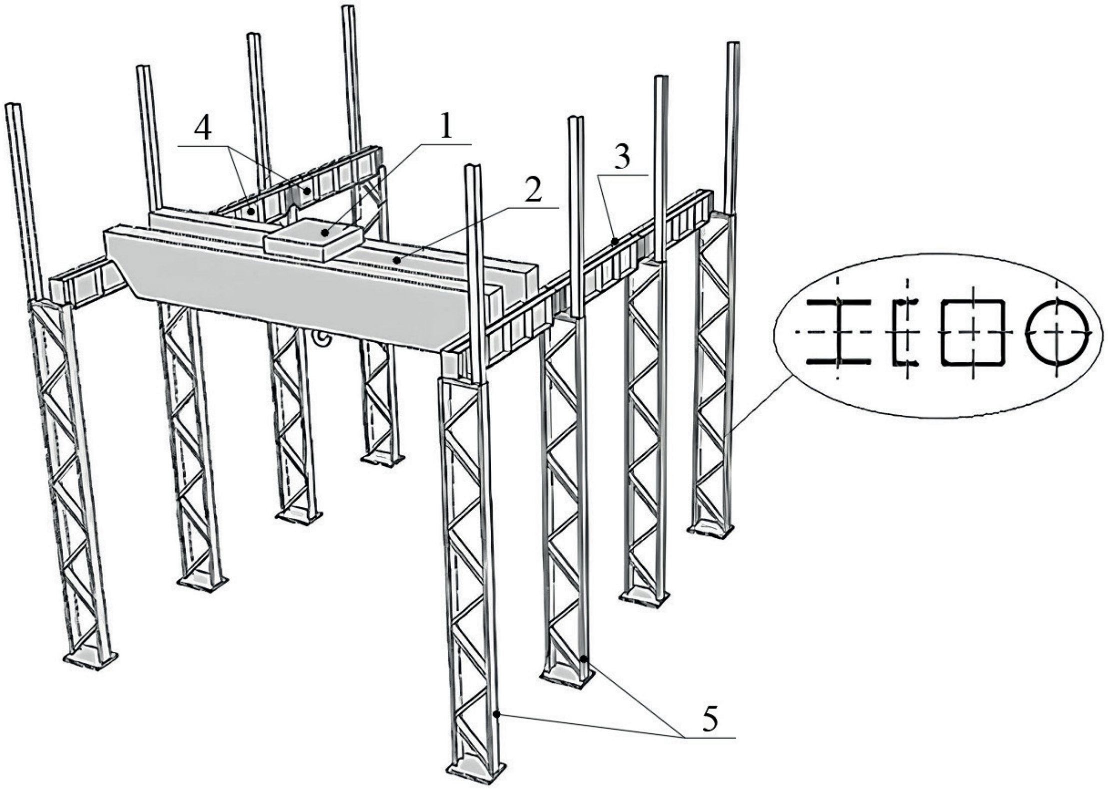


Figure 1. Configuration of load-bearing and crane structures:
1 – crane trolley; 2 – overhead crane (girder crane); 3 - crane rails; 4 - crane girders; 5 – columns

In order to ensure safe and reliable operation of the crane system, the vibrations occurring in the crane system must be damped. There are various technologies designed to reduce the amplitude of vibrations and increase the stability of the crane structure [4, 5]. These technologies include the use of damping devices, adaptive systems and advanced materials [6-9].

Hydraulic and pneumatic shock absorbers can be used to absorb vibrations [10, 11]. Adaptive systems, such as active shock absorbers or feedback systems, are able to modify their parameters in real time in response to changes in operating conditions.

Vibration protection systems consisting of flexible supports and materials with a high coefficient of internal friction play an important role in preventing vibrations. Similar systems are used in vehicles, industrial mechanisms, crane structures. Materials with increased damping include specialised elastomers, polymers with high damping capacity, active materials (e.g. piezoelectric components), vibration isolating foams, tube confined concrete, etc.

The use of steel tube confined concrete as a column material, combining the properties of concrete and steel, is a viable option when a closed-section profile is employed. This approach is widely used to create structures with increased resistance to vibrations. Concrete has a relatively high strength, fire resistance and durability, which makes it an excellent structural material. Concrete is also a good damping material. However, concrete is not an effective material for resisting cracking, which shortens the lifespan of concrete structures and requires regular maintenance. The use of a steel outer shell permits an enhanced resistance to cracking in concrete structures subjected to a combination of static loads and vibrations.

Steel tube confined concrete (STCC) is a complex structure, including a metal tube filled with concrete, which forms the inner core [12-17]. This combination exploits the distinctive characteristics of both materials, resulting in a notable reduction in steel and concrete usage, a decrease in the weight and volume of the structure, and a subsequent reduction in overall construction costs.

The shell tube, which serves the dual purpose of providing both longitudinal and transverse reinforcement, is capable of absorbing forces in all directions and at any angle [18]. The lateral pressure of the tube restrains the radial expansion of the concrete inside the tube due to the Poisson's ratio, which in turn prevents the development of micro-cracks. This significantly increases the bearing capacity of concrete, increasing its compressive strength by 50-80% [19], due to the triaxial state of stress [15]. In addition, the steel pipe is protected from loss of local secondary and general buckling.

A number of studies have been conducted by both Russian [12-14, 18-20] and foreign [21-32] authors on the subject of STCC structures, their deformation processes and the loss of stability that can occur. However, the effect of static compressive loading on the elastic-damping properties of STCC under forced vibrations has not been investigated in sufficient detail.

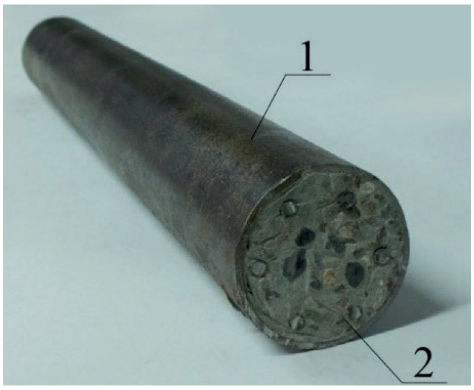


Figure 2. General view of steel tube confined concrete: 1 - outer shell (steel tube); 2 - inner filler (concrete)

This paper presents an experimental study to obtain data on the damping properties of STCC. The research findings establish the decrement and damping coefficients of vibrations, as well as the inelastic resistance coefficients of tube confined concrete.

2. STABILITY TESTS

2.1. Materials and methods

Centre compression stability tests were carried out to determine the critical compressive strength of the specimen. For this purpose, STCC specimens with a length of 700 mm and a diameter of 60 mm were fabricated. A tube made of 09G2S structural steel with 2 mm wall thickness was used as the outer shell, and concrete grade B17.5 was used as the filler.

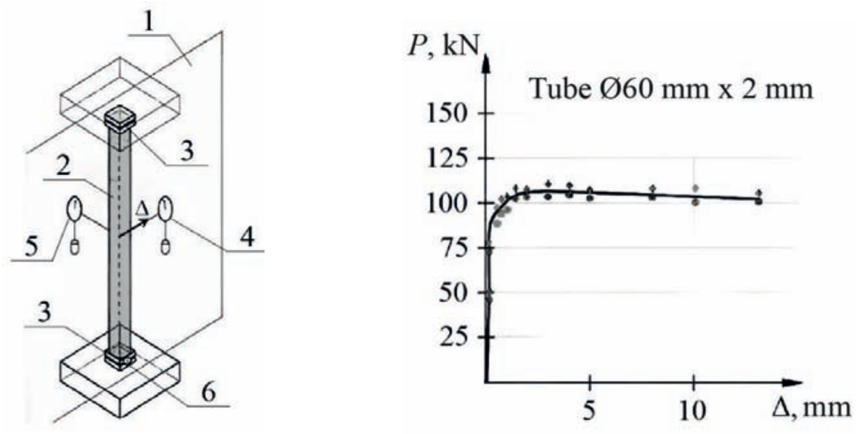
All tests were conducted on a P-125 laboratory compression machine with a maximum compressive load of 1250 kN. Each specimen was put directly between the plates of the compression machine (Fig. 3a). To ensure that the end section rotates in the bending plane (loss of stability plane) 1, the specimens 2 were supported by an additional steel plate 3 and a cylindrical support hinge 6 with an axis perpendicular to the plane 1 that is under study. The use of a cylindrical hinge helps to define the bending plane (loss of stability) of a circular specimen.

By means of two deflection gauges 4, 5 placed in two perpendicular planes (one of which is the bending plane), the horizontal displacements Δ of the average cross-section of the rod were continuously recorded with an accuracy of 0.01 mm as the load P was increased. The readings recorded by the deflection gauge 5, installed to control the displacements from the stability loss plane, were close to zero, which confirms the validity of the experiment [34].

2.2. Experimental results

The test results are presented in Fig. 3b in compression diagrams, which were used to determine the values characterising the specimen stability loss. The critical load value corresponded to the load at which the values on the deflection gauge scale begin to decrease. In compression diagrams, this value is determined by the start of bending of the corresponding curves.

Table 1 shows the values of the destruction loads for the two tube confined concrete specimens tested.



a) b)

Figure 3. Specimens tested in center compression: a) experimental setup scheme; b) compression diagram

Table 1. Critical load values for the test specimens

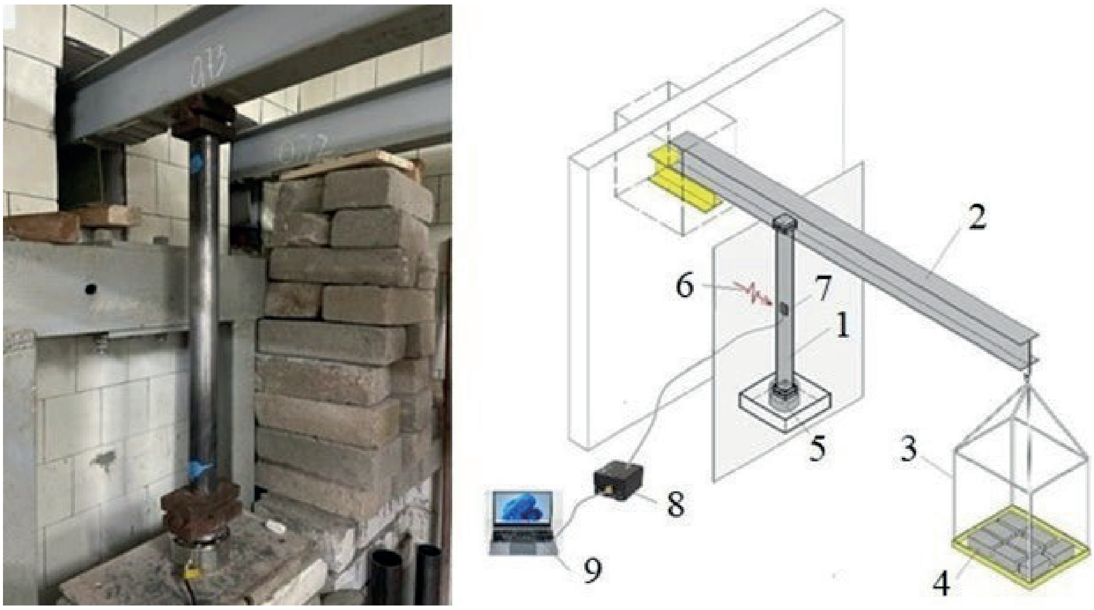
Specimens mark	Specimen no.	Critical load, P_{cr}, kN	Average critical load, $P_{cr.\,avg}$, kN
STCC 60x2.700	1	105	108
	2	111	

3. DETERMINATION OF DYNAMIC CHARACTERISTICS OF TUBE CONFINED CONCRETE

3.1. Materials and methods

The dynamic characteristics of STCC were determined through experimental investigation, based on the findings of the study of natural vibrations of the STCC specimen that was subjected to impact. The tests were carried out at different values of axial compressive forces acting on the specimens.

The setup for dynamic testing of centrally compressed specimens is shown in *Fig. 4*. Specimen 1 was hinged at both ends between the load-bearing I-beam 2 and the foundation. A basket 3 with weights 4 of varying masses was suspended from the free end of the beam 2, with a hinge located in the wall recess.



a) *b)*

Figure 4. Test setup for the study of free vibrations of centrally compressed specimens: a) general view; b) axonometric diagram

The actual load acting on the specimen (axial compressive force) includes the dead weight of the load basket and part of the gravity of the load I-beam applied to the specimen at its two-point bearing. This load was recorded using a strain gauge 5 installed under the lower support of the specimen (the values of the axial compressive force acting on the specimens during the tests are given in *Table 2*). The compressive force of the specimens did not exceed their load-bearing capacity determined by the stability tests.

Table 2. Compressive force of tube confined concrete specimens during testing

Number	Actual axial force on the specimen N_{act}, kN	Dimensionless axial force $N=N_{act}/N_{cr}$
1	1.3	0.011
2	6.8	0.057
3	12.8	0.108
4	18.7	0.157
5	24.6	0.207
6	30.6	0.257
7	36.5	0.307

The generation of transverse vibrations in the specimen was achieved at each stage of loading using a spring-loaded hammer 6. A triaxial accelerometer 7 of type TBA with a mass of approximately 50 g was used to record the vibrations (the insignificant mass of the accelerometer did not affect the accuracy of the measurements). The accelerometer was fixed in the mid-section of the specimen. The signal from the accelerometer was fed through the signal processing module 8 (matching amplifier and analogue-to-digital converter) to a personal computer 9 for registration and subsequent processing of the measurement results.

Free decreasing vibrations were generated in the specimen during a single impact. To illustrate the test results, *Figure 5* shows oscillograms of decreasing vibrations in the form of diagrams of the specimen mid-section displacement *A* over time *t*, obtained at two extreme values of axial compressive force N_1 = 6.8 kN (*Fig. 5a*) and N_6 = 36.5 kN (*Fig. 5b*).

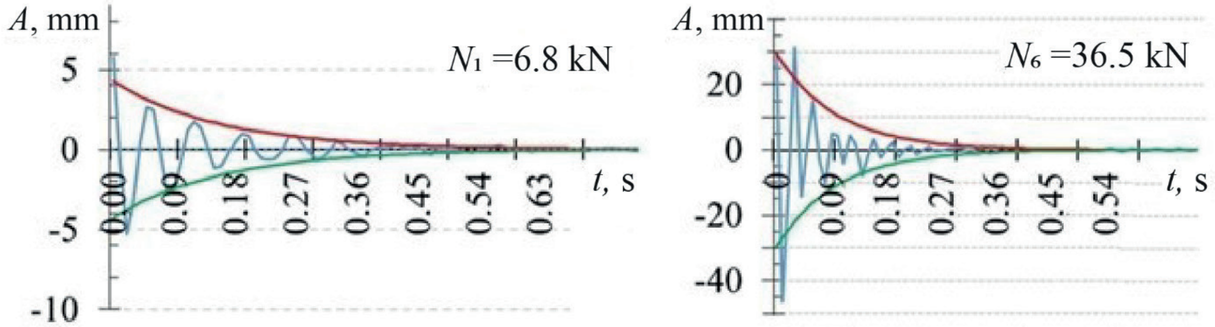


Figure 5. Graphs of bending vibrations of a tube confined concrete specimen loaded with axial compressive force N at impact: a) N_1 = 6.8 kN; b) N_6 = 36.5 kN

3.2. Experimental results

The analysis of the obtained oscillograms has demonstrated that these vibrations are highly analogous to those observed in linear systems with viscous friction, where the period of natural vibrations *T* is largely independent of the amplitude *A*. Moreover, the first natural frequency of bending vibrations of the STCC specimen $\omega = 2\pi/T$ increases with increasing axial compressive force *N* acting on the specimen (*Fig. 6*). The authors of [35-37] also observed a correlation between an increase in frequency and an increase in compressive stress. It is important to highlight that this behaviour in the compression of STCC differs from the established concepts regarding the behaviour of isotropic continuous media [38, 39]. This phenomenon may be attributed to the characteristics of the composite material and the specific interactions between the core and the shell of the STCC.

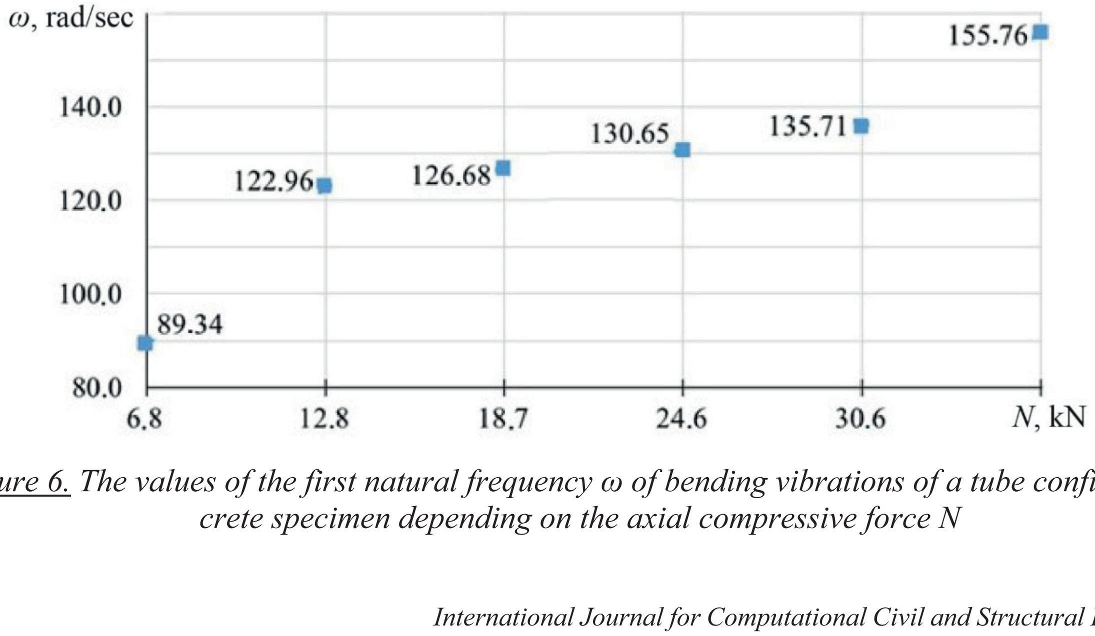


Figure 6. The values of the first natural frequency ω of bending vibrations of a tube confined concrete specimen depending on the axial compressive force N

These vibrations can be described with a reasonable degree of accuracy by the well-known law of free, decreasing vibrations of linear systems with viscous friction:

$$x(t) = A(t)e^{-\beta t}\cos(\omega t)\,, \qquad (1)$$

where *A(t)* - amplitude of vibrations, m; β - logarithmic damping ratio, sec^{-1}; ω - circular oscillation frequency, rad/sec; t - time, sec.

According to the results presented in *Fig. 6*, we can see that an increase in the axial force leads to an increase in the natural frequency and, consequently, to an increase in the elastic properties of the structure. In the case of a linear hinged beam, the natural frequency of bending vibrations is determined by the following formula [40]:

$$\omega = \frac{\pi^2}{l^2}\sqrt{\frac{EJ}{\rho F}} = \frac{\pi^2}{l^2}\sqrt{\frac{EJ}{m_l}}\,, \qquad (2)$$

where E - average (reduced) elastic modulus of the STCC specimen material, N/m^2; J - moment of inertia of the specimen cross-section, m^4; ρ - reduced density, kg/m^3; F - cross-sectional area of the specimen, m^2; m_l - linear mass, kg/m; l - specimen length, m.

From equation (2), which is derived from the experimentally obtained value of the natural frequency of vibration, we can calculate the reduced coefficient, which accounts for the elasticity of the material and the influence of the axial compressive force N_{act} of the specimen.

$$E_N = \frac{\omega^2 m_l l^4}{\pi^4 J} \qquad (3)$$

In this instance, the alteration of the elastic properties of the structure as a consequence of the axial compressive force is accounted for by a conditional change in the value of the reduced E_N coefficient.

The proposed methodology was employed to calculate the values of the E_N coefficient for a distributed mass of the specimen, resulting in m_l = 0.01 t/m and $J = \pi D^4/64 = 6.36 \cdot 10^{-7}$ m^4. These values are presented in *Fig. 7*.

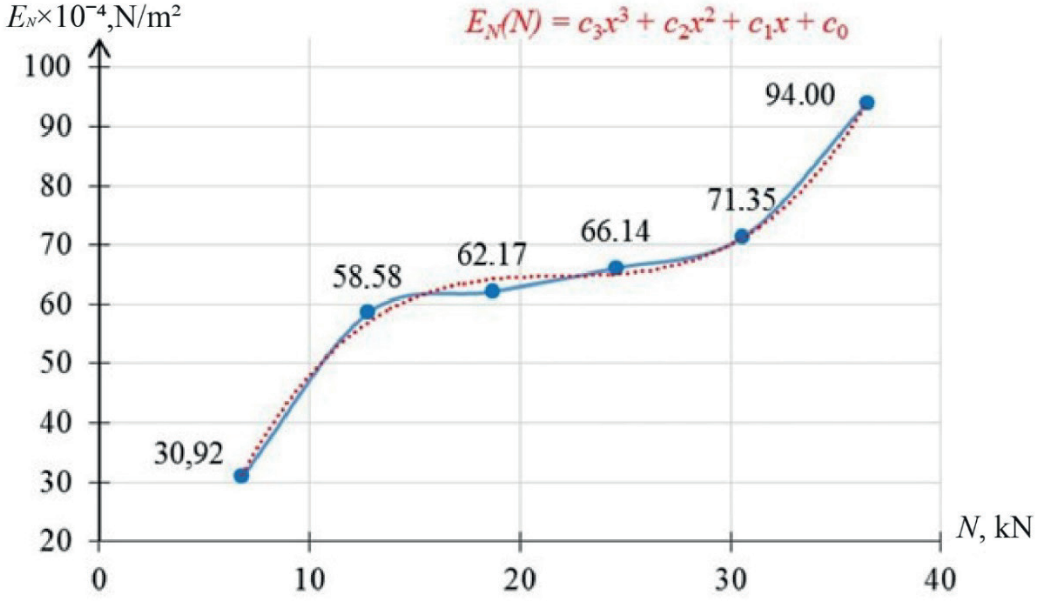


Figure 7. A graph of the reduced coefficient depending on the axial load with an approximating monotonic function $E_N(N)$

As illustrated in *Fig. 7*, the graph demonstrates that the value of the reduced coefficient rises in conjunction with an increase in the axial compression force. This outcome reflects the physical meaning of the coefficient, which is influenced by the axial compression force. Subsequent studies may use the obtained value to determine the frequency of natural vibrations of STCC structures produced from materials of other brands and with a section different from that under consideration.

Excluding the action of the axial force on the tested specimen, we obtain a reduced coefficient that fully reflects the elastic properties of the material and is in fact the average (reduced) modulus of elasticity E, which is confirmed by the results obtained in [32].

The logarithmic damping ratio included in the equation of motion (1) can be calculated as the average of several logarithmic damping ratios from the graphs shown in *Fig. 5*. In order to level local errors, instead of two neighbouring vibration amplitudes x_j, x_{j+1}, the ratio of vibration amplitudes x_j, x_{j+s} after several s periods was used in this work (*Fig. 8*). In the case under consideration, the logarithmic damping ratio β was determined on several n different sections of the oscillogram, offset one from another. Each section consisted of five periods, which explains the presence of the coefficient 0.2 in the equation. Then the average value of the logarithmic damping ratio $\bar{\beta}$ is calculated by the following formula:

$$\bar{\beta} = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{0.2}{T} ln \frac{x_j}{x_{j+5}}\right)_j , \qquad (4)$$

where x_j, x_{j+5} are the peak values, at the boundaries of the time interval (t_j, t_{j+5}), m; n is the number of waveform sections taken to calculate damping ratio; T is the period, sec.

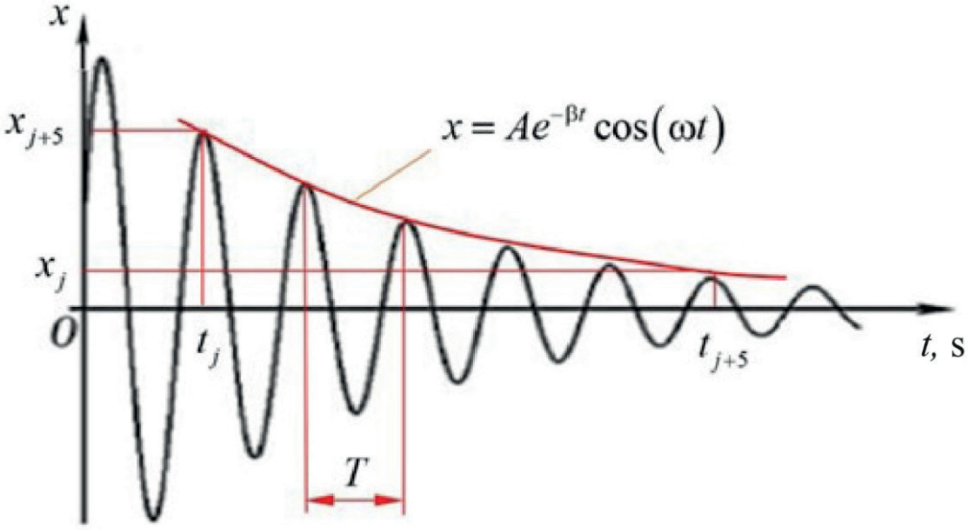


Figure 8. Determining the damping ratio

The processing of the obtained oscillograms yielded the following values for the logarithmic damping ratio of the STCC specimen under the two lowest and highest compressive forces: $\bar{\beta}$= 6.20 at N_1 = 6.8 kN and $\bar{\beta}_6$ = 10.21 at N_6 = 36.5 kN. Thus, it is found that the damping ratio depends on the axial compressive force of the STCC.

4. FORCED VIBRATIONS

In the context of forced vibrations, the damping behaviour of support structures are characterised by the inelastic resistance coefficient γ. This coefficient accounts for the dissipation of vibration energy due to internal friction within the material, with the resulting values determining the amplitudes of vibrations in near-resonant zones. This coefficient is a material constant and is directly related to the damping ratio and natural frequency of the system:

$$\gamma = \frac{2\bar{\beta}}{\omega} = \frac{\bar{\beta}T}{\pi} \tag{5}$$

The amplitude of forced vibrations is dependent upon the dynamic coefficient μ, which for linear systems with one degree of freedom is described by the following formula [35]:

$$\mu = \frac{1}{\sqrt{(1-\lambda^2)^2 + \gamma^2\lambda^2}}, \tag{6}$$

where $\lambda = \Omega / \omega$ is the ratio of the circular frequency Ω of the stimulus and the natural frequency of the system ω; γ is the coefficient of inelastic resistance of the material, taking into account the forces of internal friction.

The following values of the inelastic compressive force coefficient were obtained for the lowest and highest compressive forces (see *Table 3*).

Table 3. The value of the inelastic resistance coefficient

	Compression force	Damping ratio $\bar{\beta}$, sec^{-1}	Natural-vibration frequency ω, rad/sec	Coefficient of inelastic resistance γ, rad^{-1}
1	N_1=6.8 kN	6.20	89.34	0.139
2	N_6=36.5 kN	10.21	158.5	0.129

The calculated values for different values of compressive forces acting on the sample exceed the coefficient of inelastic behavior for concrete and reinforced concrete γ_{reinf} = 0.1 rad^{-1}, as well as for steel γ_{stl} = 0.12 rad^{-1}.

The obtained value of the inelastic resistance coefficient (γ_1=0.139 rad^{-1} and γ_6=0.129 rad^{-1}) differ by no more than 7%. At the same time, exceeding similar values for reinforced concrete by 30-40% results in a notable reduction in the dynamic coefficient at the resonant frequency (Fig. 9).

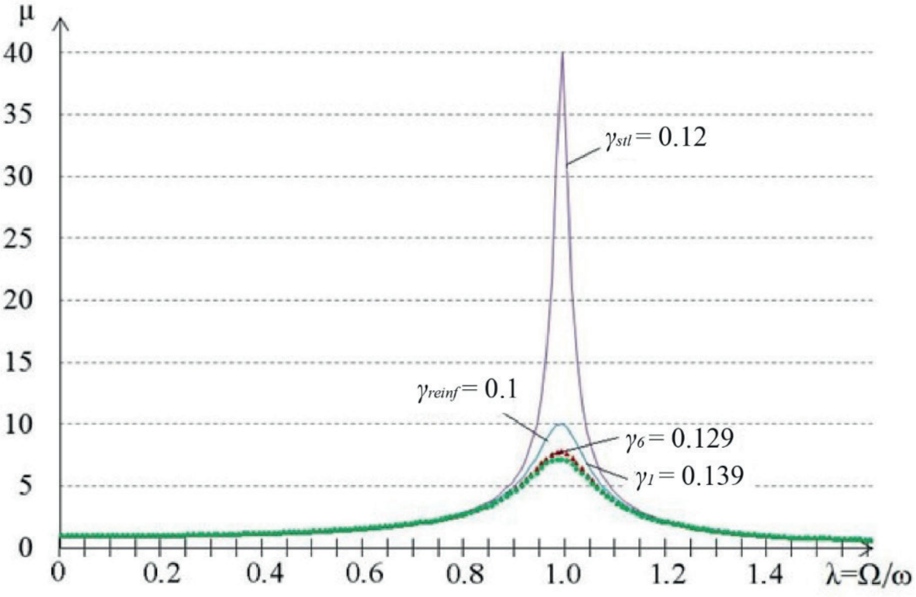


Fig. 9. Resonance curves of various materials: γ_{reinf} is the coefficient of inelastic resistance of reinforced concrete, γ_{stl} is the coefficient of inelastic resistance of steel, γ_1, γ_6 are the coefficients of inelastic resistance of tube confined concrete

5. CONCLUSIONS

In conclusion, the present work demonstrates the impact of axial compressive loads on the quantitative characteristics of elastic and damping behaviour in tube confined concrete. It was determined that internal stresses have no notable impact on the inelastic behaviour coefficient (≤7%) and, consequently, on the damping behaviour of the materials.

Additionally, tube confined concrete structures exhibit enhanced damping behaviour in comparison to steel and reinforced concrete structures. The damping parameters of tube confined concrete have been observed to exhibit characteristics that exceed the values of other materials by up to 40 per cent.

Due to its high strength and rigidity, tube confined concrete structures are able to withstand significant loads and ensure durability. Furthermore, their damping capacity helps to diminish vibrations under dynamic loads, which is of particular significance in various crane structures, motorway and railway bridges, and oil and gas platforms that are subjected to seismic and dynamic forces. The investigation of this subject matter has the potential to give rise to innovations and enhancements in the fabrication of tube confined concrete structures, which in turn could advance the development of engineering solutions that are more efficient and secure.

6. ACKNOWLEDGEMENTS

The work was conducted within the framework of the fundamental scientific research programme of the Institute of Applied Physics of the Russian Academy of Sciences (IAP RAS) for the period 2024-2026 (FFUF -2024-0031, no. R&D 1023032800130-3-2.3.2).

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