Research of the combination of energy-saving technologies and green materials as key factors of sustainable building design

Российский университет дружбы народов

Student： Huang Jueru

Supervisor： Dmitry Koroteev

Direction: 2.1.1 Строительные конструкции, здания и сооружения

Content

1.1 Research Background

Environmental Issues

- **Ecological issues:** Carbon emissions from construction account for **30-40%** of global carbon emission
- **Steel structures:** High-strength and recyclable, but associated with high carbon emissions (≈ 2.4 tons of CO_2/ton of steel).
- **Transformation:** Sustainable building

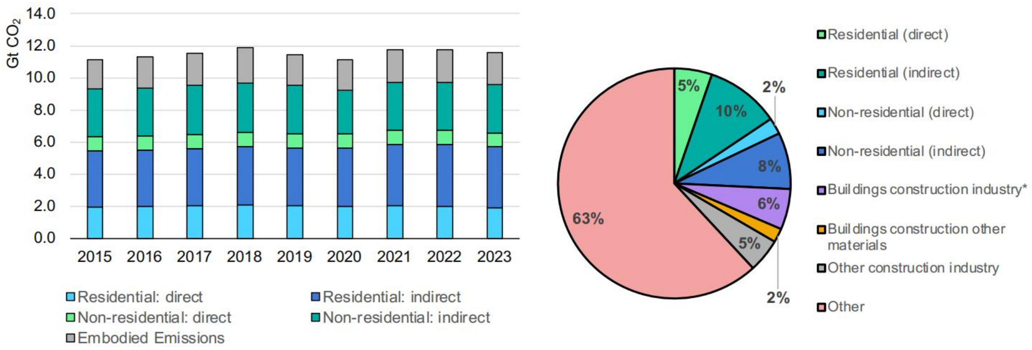


Figure ES.1. CO_2 emissions in buildings 2010–2023 (left) and share of buildings in global energy and process emissions in 2023 (right) (International Energy Agency 2024a)

Structural safety

Research Gap

Green materials

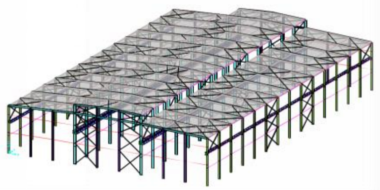
Integrating energy-saving technologies and green materials to optimize sustainable building design

Research Objective

1.2 Research Direction

Scope

- Material: **Q460C**
- Technology: FEM+ LCA +3D printing (for scaled model validation)
- Project: Steel structure, single-story factory building
- Joint: column-beam, column base



Significance

- Provide a “safety–low carbon” collaborative design method for green steel structures
- Establish a quantifiable chain of “performance → material → carbon”

Research innovations

1.Propose an integrated “refined simulation – LCA” analysis framework
2.Reveal the safety–low carbon synergy mechanism of high-strength steel joints
3.Extract five design principles and an engineering decision framework
4.Complete validation from laboratory joints to real engineering projects

1.3 Research tasks

Hypothesis

By using **Q460C** high-strength steel and optimized details (end beam + connection plate + box-type stiffening), **material consumption** and **carbon emissions** can be significantly reduced without decreasing – even while increasing – **structural safety**

Research Task

1.Establish and validate refined finite element **models**

2.Perform static and quasi-static loading analyses, **comparing** baseline and optimized schemes

3.Quantify carbon reduction benefits using **LCA**

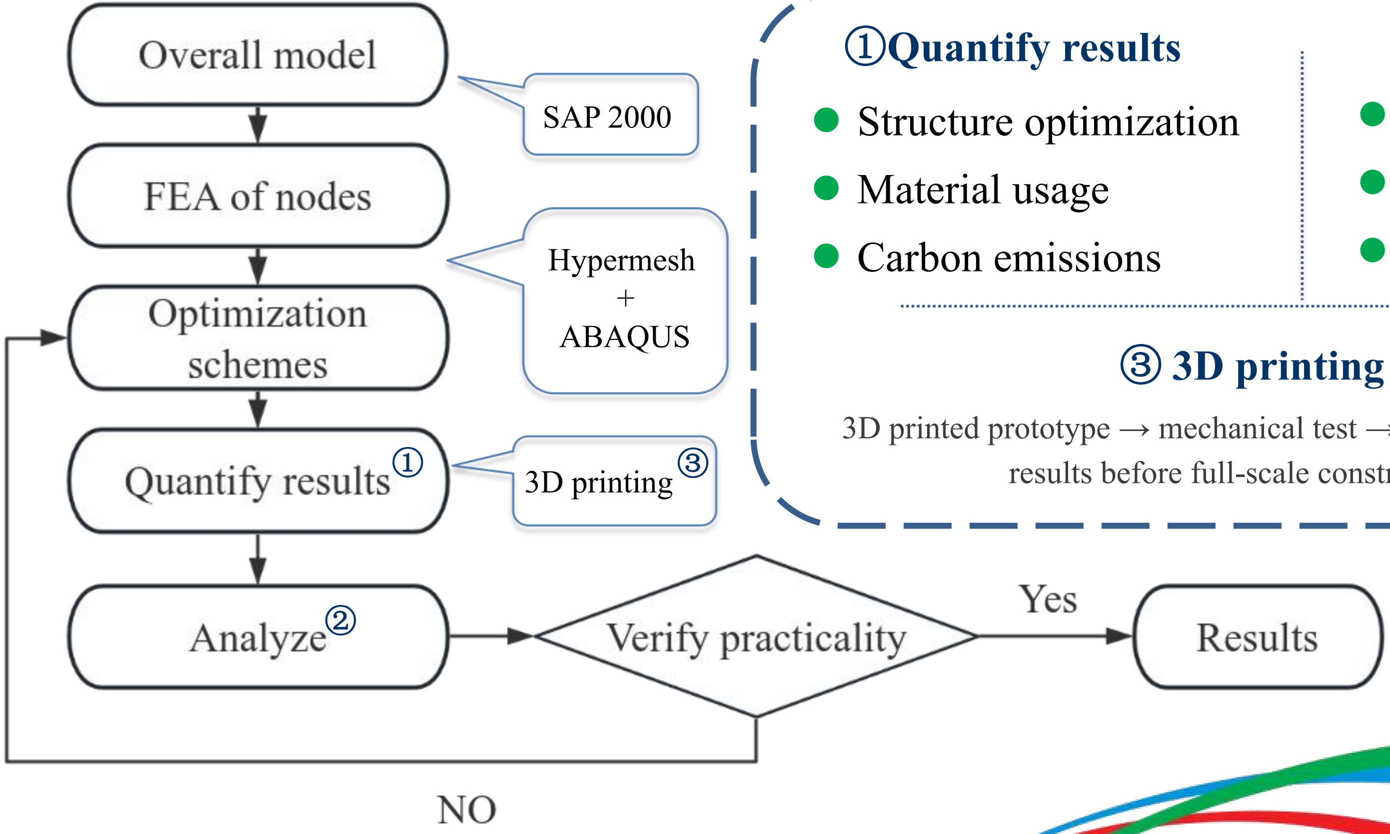
4.Verify **feasibility** through a real engineering project

Expected result

- Optimized joint **capacity** increase > 20%, **failure** mode changes from brittle to ductile

- **Steel** consumption **reduced** by 20–25%, **carbon** reduction > 65%

2.1 Research route



①Quantify results

- Structure optimization
- Material usage
- Carbon emissions

②Analyze

- Feasibility
- Versatility
- Economy

③ 3D printing

3D printed prototype → mechanical test → validate numerical results before full-scale construction

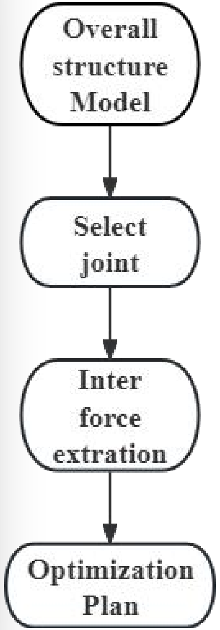
2.2 Research method- FEM

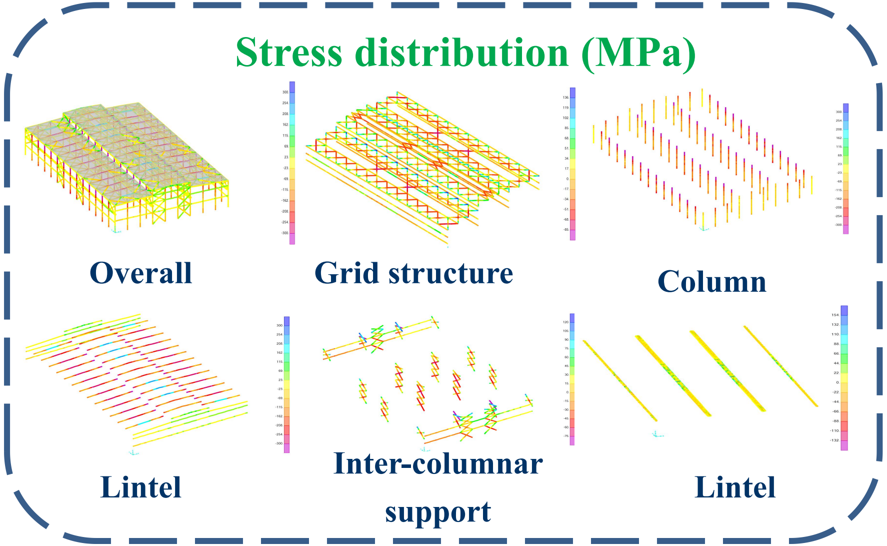
Global Structural Analysis (SAP2000)

●Prototype: span **24m**, column spacing **6m**, seismic intensity **8°**
●Critical load casesRefined Joint FEM (Hypermesh+ABAQUS): **wind** load / **crane** load
●Extracted joint forces:
Beam-column: **M=402 kN·m, V=200 kN**
Column base: **N=585 kN, V=88 kN, M=4852 kN·m**

Refined Joint FEM (Hypermesh+ABAQUS)

●**Element types:** S4R (steel), C3D8R (concrete), B31/T3D2 (bolts/rebar)
●**Material models:** bilinear hardening (Q355/Q460C), damage plasticity (C30)
●**Validation vs. Wu et al. (2025):** initial stiffness error 2.6%, ultimate capacity error 2.5%





2.3 Research Method-LCA

System Boundary

Defined as**“cradle-to-gate”**, covering the phases of raw material extraction, transportation, and component manufacturing, focusing on the production phase.

Functional Unit (FU)

A**single steel structure node**. This unit serves as the basis for quantifying and comparing the environmental impacts of different structural designs.

Carbon Factor Sources & Values

Sources: Ecoinvent v3.9, China Product Life Cycle Database (CNLCD)

• Q355 Steel: 2.40 kg CO_2-eq/kg | Q460C (BF): 2.60 kg CO_2-eq/kg
• C30 Concrete: 0.12 kg CO_2-eq/kg

★ Recycled Steel (Electric Furnace): 0.90 kg CO_2-eq/kg

GWP Calculation Formulas

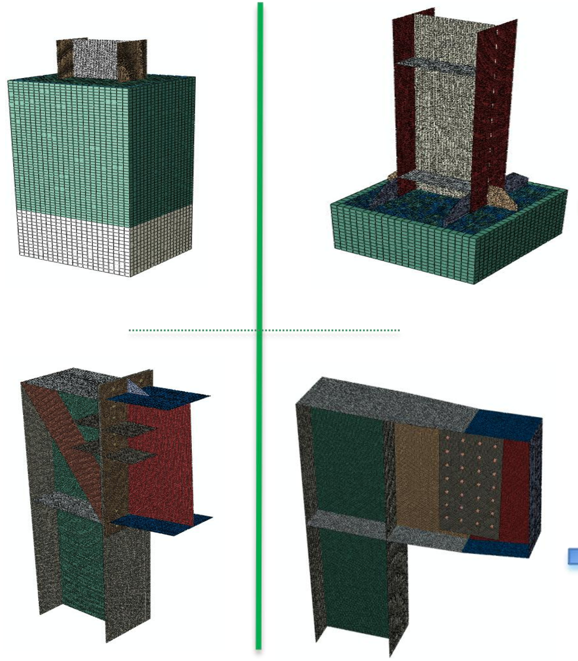
$$GWP = \Sigma\ (m_i \times EF_i)$$

where m_i = mass of material i, EF_i = emission factor of i (Lines 2-10)

$$\Delta GWP = GWP\_base - GWP\_opt$$

where ΔGWP = emission reduction, base = original design, opt = optimized design (Lines 2-11)

3.1 Optimization schemes

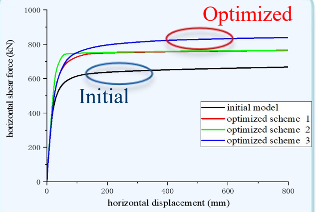


Traditional **Optimization**

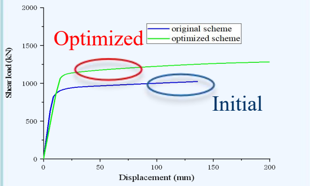
Optimization results

1. Best scheme: Q460C + box-type stiffening (Scheme 3, Table 22, p.155)
2. Steel usage 551.7 kg (↓18.6%), concrete 950 kg (↓67%), ultimate load 796 kN (↑25%)
3. Carbon reduction: baseline 1969.4 kg → optimized 610.5 kg CO_2-eq (↓69.0%)

1. Best scheme: Q460C + end beam + connection plate + flange welding (As shown in pic)
2. Weight 0.521 t (↓22.9%), capacity increase 11.8%
3. Carbon reduction: baseline 1.622 t → optimized 0.469 t CO_2-eq (↓71.1%)



Bearing Capacity Curve

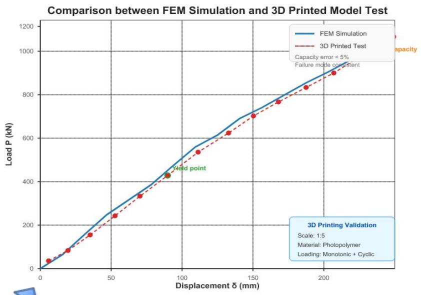


Load-displacement curve

3.2 Hypothesis verification

Hypothesis	Verification	Results
Bearing capacity increase	Beam-column joint ↑： 24.1% Column base joint ↑： 25%	☑
Failure mode changes from brittle to ductile	Bolt shear → end beam/base plate yielding	☑
Material consumption	Steel↓： 18.6–22.9% Concrete ↓： 67% Carbon ↓： 69–71%	☑
Good seismic performance	Plump hysteresis curves Equivalent damping coefficient >0.25, Plastic hinge relocation	☑

3.3 Engineering verification-3D printed joint



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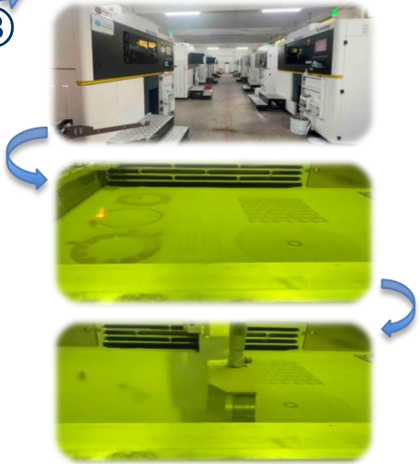
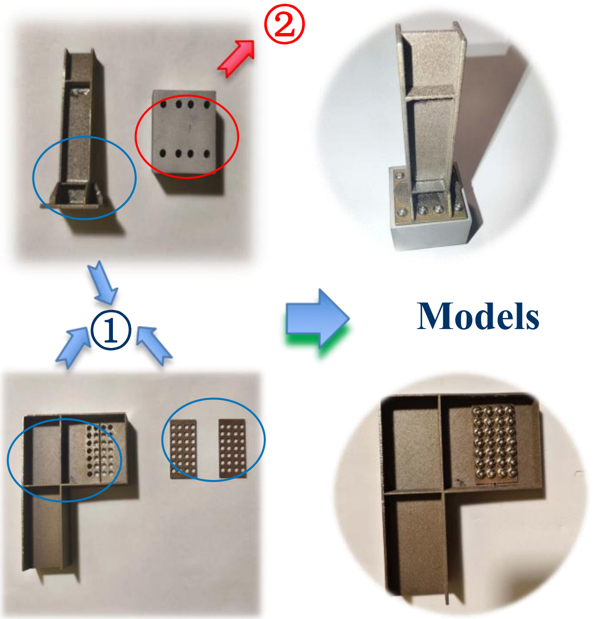


3D printer

- **SLM** (laser powder fusion technology)
- **Materials:** ① **316L+Metal powder**
  ② **$AlSi_{10}Mg$** (Aluminum alloy)
- **Objective:** Before the real engineering application, the mechanical test is carried out through the 3D printing of the scaled node model to further verify the accuracy of finite element analysis.
- **Results:** The bearing capacity and destruction mode of the 3D printed model are highly consistent with the finite element simulation results **(error <5%**→ pic③**)**
- **Scale：** Column-Beam: **19:1**
  Column base: **30:1**
  (model height=10cm)



3.4 Engineering verification- in project

Project Overview

●**Location:** Jiangxi Province
●**Optimized content:** A total of **8 beam-column joints** and **4 column base joints** were upgraded to achieve lightweight structural modifications.

Application Effect

- **Steel** consumption: reduced by **25.9%**
- **Carbon emission** reduction: approximately **1.71 t** CO_2
- **Economic** benefits: Cost reduction of **18%**
- **Duration**: Reduced by **2 days**

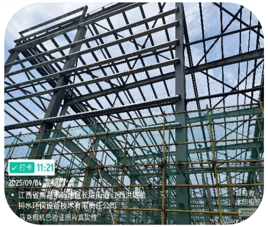
Review Verification

Through specialized review (Reports in pic):
1. Special fire safety review
2. Green Building Audit
3. Special Review of Carbon Emissions

① ②

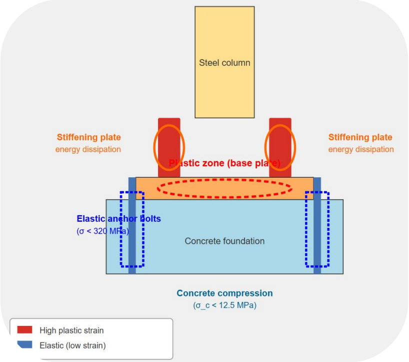
③



Summary: This project successfully validated the engineering **feasibility** of the research findings, demonstrating outstanding performance in **material conservation** and project **duration** reduction, while achieving significant **carbon emission** reduction outcomes. It provides a **replicable** reference model for similar sustainable building renovations.

4.1 Safety-Low Carbon Synergy Mechanism



Material level

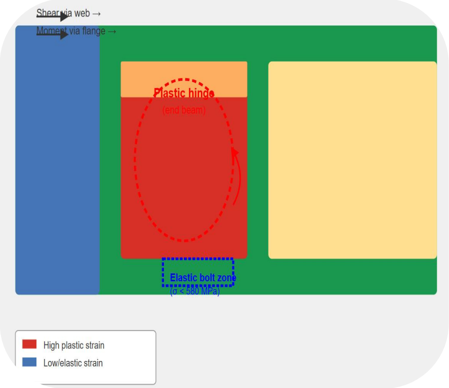
Q460C strength-ductility balance (equivalent plastic strain 0.12–0.18)

Force transfer level

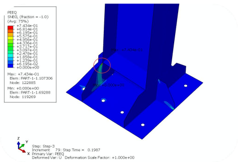
Decoupling – web shear + flange bending

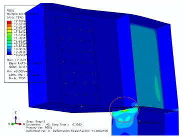
Failure mode level

Brittle → ductile, plastic hinge outward



Distribution of plastic strain under extreme limits





Plastic strain at the limit moment of the new scheme

This three-level synergy enables simultaneous improvement in structural safety and carbon reduction.

4.2 Comparison of research results

Comparison Object	Joint Type	Capacity Increase	Ductility μ	Carbon Reduction	Key Advantage of This Research
Wang Yan et al. (2014)	Q690 end-plate	~30%	3.2–3.8	Not reported	Higher ductility (μ = 4.6)
Shi Gang et al. (2017)	Bolted-welded hybrid	–	Moderate	Not reported	"End beam" configuration moves weld away from high-stress zone, avoids brittle fracture
Li Guoqiang et al. (2023)	Semi-rigid replaceable column base	~600 kN	3.5	Not reported	Box-type stiffened column base: +32.7% capacity (796 kN), concrete reduced by 67%
Existing LCA studies	Various steel joints	–	–	Not directly linked to performance	First to establish a quantifiable "performance → material → carbon" chain
This research	Q460C + force decoupling (beam-column & column base)	+24.1% (beam-column) / +25% (column base)	4.6	69–71% (recycled steel scenario)	Simultaneous improvement in capacity, ductility, and carbon reduction

Conclusion

For the first time, simultaneous quantitative improvements in **bearing capacity**, **ductility**, and **carbon emission** reduction are achieved.

4.3 Research Limitations and Future Prospects

Limitations of the study

- Initial geometric **imperfections** and welding residual **stresses** not considered
- LCA only cradle-to-gate, excluding **operation** and **demolition**
- **Extreme conditions** such as fire, fatigue, and post-earthquake fire not studied

Future Research Perspectives

- Multi-hazard coupled experiments and simulations (**earthquake** + **fire**)
- Combined LCA + **LCC** optimization
- **Machine learning**-assisted parameter optimization
- **Statistical performance** of recycled high-strength steel
- Development of **BIM-FEA-LCA** integrated tools
- **Topology** optimization node design combined with 3D printing

Publications

- **Публикации в изданиях, включенных в перечень рецензируемых научных изданий:**

1.Коротеев, Д. Д. Прогнозирование энергозатрат в системах управления домашним энергопотреблением с применением метода машинного обучения / Д. Д. Коротеев, Т. А. Коротеева, *Ц. Хуан* // Строительство и архитектура. – 2023. – Т. 11, № 2. – С. 6. – DOI 10.29039/2308-0191-2023-11-2-6-6.
2.Коротеев, Д. Д. Исследование методов энергосбережения при проектировании выстровозводимых зданий из лёгких стальных конструкций / Д. Д. Коротеев, *Ц. Хуан*, И. А. Скуратова // Строительное производство. – 2024. – № 4. – С. 12-17. – DOI 10.54950/26585340_2024_4_12.

- **Статьи, опубликованные в журналах, индексируемых в международных реферативных базах Scopus и Web of Science:**

3.*Huang, Jueru*. Artificial intelligence for planning of energy and waste management / J. Huang, D. D. Koroteev // Sustainable Energy Technologies and Assessments. – 2021. – Vol. 47. – P. 101426. – DOI 10.1016/j.seta.2021.101426.
4.*Huang, Jueru*. Smartphone-based study of cement-activated charcoal coatings for removal of organic pollutants from water / J. Huang, D. D. Koroteev, M. Zhang // Construction and Building Materials. – 2021. – Vol. 300. – P. 124034. – DOI 10.1016/j.conbuildmat.2021.124034.
5.*Huang, Jueru*. Develop a molecular dynamics approach to simulate the single-/multi-layer CsGeX3 (X = I, Cl, and Br) perovskite stress-strain structure at different temperatures and pressures for solar cell in building energy management / Ju. Huang, D. D. Koroteev, M. Rynkovskaya // Engineering Analysis with Boundary Elements. – 2022. – Vol. 145. – P. 396-403. – DOI 10.1016/j.enganabound.2022.09.027.
6.*Huang, J*. Building energy management and forecasting using artificial intelligence: Advance technique / J. Huang, D. D. Koroteev, M. Rynkovskaya // Computers & Electrical Engineering. – 2022. – Vol. 99. – P. 107790. – DOI 10.1016/j.compeleceng.2022.107790.
7.*Jueru. Huang*. Machine learning-based demand response in PV-based smart home considering energy management in digital twin / J. Huang, D. Koroteev, M. Rynkovskaya // Solar Energy. – 2023. – Vol. 252. – P. 8-19. – DOI 10.1016/j.solener.2023.01.044.
8. *Jueru. Huang*, W. Zonghui, D. D. Koroteev, M. Rynkovskaya. Energy efficiency security in urban areas: Challenges and implementation // Sustainable Cities and Society. – 2024. – Vol. 107. – P. 105380. – DOI 10.1016/j.scs.2024.105380.
9.Wei Yu, Liuyan Wang, Chunfeng Yang, *Jueru Huang*, Seyed Mohsen Sadeghzadeh. Multimetallic MOF-74-M reinforced lightweight concrete: Enhanced impact resistance and environmental durability. // Journal of Materials Research and Technology.-2025.-Vol. 38. -P.4064-4077. DOI 10.1016/j.jmrt.2025.08.259.

- **Статьи, опубликованные в сборниках трудов конференций:**

10.Koroteev, D. D. Construction cost control and duration analysis of rehabilitation project / D. D. Koroteev, *J. Huang*, M. Kamrunnaher // Journal of Physics: Conference Series, Moscow, 14–16 октября 2020 года. – Moscow, 2020. – P. 012012. – DOI 10.1088/1742-6596/1687/1/012012.
11.M. Kharun, D. D. Koroteev, M. Hemati Bahar [et al.] /Behavior of conventional and fibered concrete shear walls during earthquake, an analytical simulation in SAP2000 / // Journal of Physics: Conference Series, Moscow, 14–16 октября 2020 года. – Moscow, 2020. – P. 012033. – DOI 10.1088/1742-6596/1687/1/012033.
12.The additive manufacturing in road construction as factor of its sustainability in conditions of climate change and hydrological catastrophe / T. A. Suetina, D. D. Koroteev, A. I. Koreneva, *Jueru. Huang* // IOP Conference Series: Materials Science and Engineering. – 2021. – Vol. 1159, No. 1. – P. 012015. – DOI 10.1088/1757-899x/1159/1/012015.

Thank you