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Review of Research on Extraordinary Mechanical Properties and Engineering Seismic Toughness of NPR Materials

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Abstract: Negative Poisson 's ratio (NPR) material has the unique mechanical properties of lateral expansion during tension, and has high toughness, high strength, large deformation capacity under constant resistance and excellent energy absorption performance, which provides a new way to improve the seismic performance of engineering structures. This paper systematically summarizes the research and application progress of such materials (such as NPR anchors / cables, NPR steel bars) in seismic engineering. The key mechanical behaviors (negative Poisson 's ratio effect, constant resistance energy absorption, high shear strength) are summarized, as well as the core role in geotechnical support, structural reinforcement and isolation barrier. Through static / dynamic tensile, cyclic shear and shaking table model tests, combined with numerical simulation methods such as ABAQUS and LS-DYNA, it is confirmed that NPR materials have significant effects in efficiently dissipating seismic energy, coordinating large deformation, reducing surrounding rock damage and reducing structural dynamic response. Although some achievements have been made in engineering practice, the performance degradation of this material at high temperature, the decrease of constant resistance under cyclic loading and the high preparation cost are still the main bottlenecks in the development of this field. In the future, these obstacles need to be broken through in this technology to promote the wide engineering application of NPR materials in earthquake resistance and disaster prevention of major projects.

Keywords: NPR Material, Seismic Engineering, Energy Absorption, Negative Poisson 's Ratio Effect, Constant Resistance.

1. Introduction

The occurrence of earthquake disasters often has the characteristics of strong suddenness and great destructive power, and will continue to endanger the safety of personnel and property and the stability of infrastructure. The existing seismic design methods mainly rely on the strength, stiffness and ductility of the structural members, and suppress the damage of the structure by absorbing and dissipating the energy input by the earthquake. However, in the face of increasingly complex engineering challenges and strong earthquakes, traditional material and structural system schemes face severe challenges in terms of energy consumption efficiency, deformation coordination, and centralized damage control. Therefore, the development of new materials and structural technologies with excellent mechanical properties and efficient energy dissipation mechanisms is particularly important for improving the seismic performance of engineering structures.

In recent years, materials with negative Poisson 's ratio (NPR) effect (also known as expansion materials) have attracted extensive attention from researchers in the field of engineering earthquake resistance due to their unique mechanical behavior. In the field of rock mechanics with macroscopic scale of 10-2 ~ 10m, academician He Manchao first proposed the key problem of mechanical behavior of negative Poisson 's ratio structure, and successfully developed a new type of high constant resistance and large deformation bolt / cable (NPR bolt / cable) with negative Poisson 's ratio effect (NPR). The breakthrough of this technology provides an important solution for the active control, dynamic monitoring and risk prediction of deep rock burst, rock burst and other dynamic disasters and major landslides[1]. NPR materials are different from conventional materials in transverse shrinkage (positive Poisson 's ratio) during tension. When NPR materials are subjected to uniaxial tension or compression, their transverse dimensions will exhibit abnormal expansion or shrinkage (i.e., transverse expansion during tension and transverse shrinkage during compression). Studies have shown that negative Poisson 's ratio materials exhibit better performance than traditional positive Poisson 's ratio materials in many aspects such as impact resistance, shear resistance, yield strength, energy absorption and dissipation capacity[2[5].

2. The Basic Properties and Mechanical Mechanism of NPR Materials

2.1. Basic Characteristics

(1) In terms of strength and toughness indicators, NPR steel bars / anchors show excellent performance. Its ultimate tensile strength can reach 1100 MPa, and the uniform elongation is greater than 40 %, which is significantly better than that of conventional HRB400 steel bars. Compared with conventional HRB400 steel bars, the trace enrichment of Cr, Ni and Cu elements in NPR steel bars helps to improve their strength, hardness and corrosion resistance[6]. The experimental data confirm that under the same reinforcement conditions, the ultimate bearing capacity of the beam with NPR steel bars is 133 % higher than that of the HRB400 steel bar[7]. This synergistic mechanism of high strength and high toughness endows the structure with the ability to efficiently dissipate energy through significant plastic deformation under earthquake, effectively delaying the process of failure development, and ultimately ensuring the improvement of seismic performance of engineering structures. see Fig. 1.

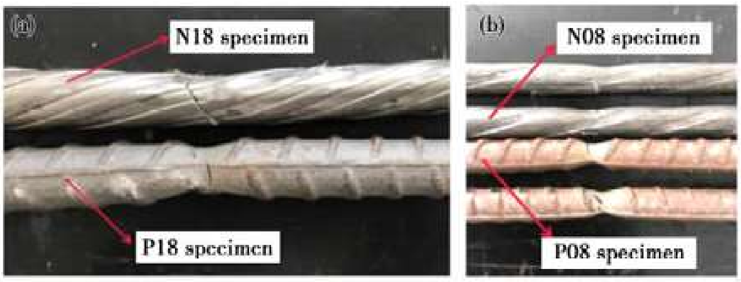

Fig. 1 Comparison of tensile necking phenomena of (a) 18 mm steel bar and (b) 8 mm steel bar [6]

(2) Negative Poisson 's Ratio (NPR) : As an iconic mechanical behavior of NPR materials different from conventional materials, the negative Poisson 's ratio effect reflects its unique deformation response. Under axial tension or compression load, this kind of material shows abnormal size change in the transverse direction : transverse expansion occurs during tension, while transverse shrinkage occurs during compression [8]. see Fig. 2.

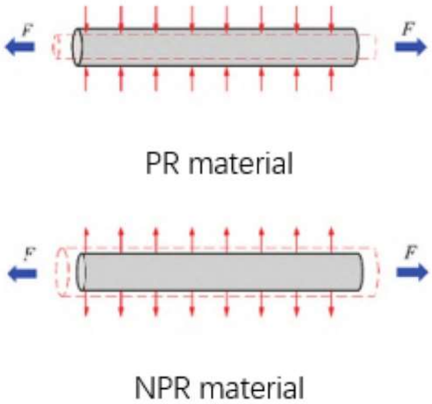

Fig. 2 Schematic diagram of deformation of PR material and NPR material[8]

The core of this effect is that the ratio of transverse strain to axial strain is negative. The Poisson 's ratio of the material has scale-invariant properties, which can be reflected as the overall mechanical response at the macro-structural level[9], and can also be derived from the inherent characteristics of the internal microstructure of the material [10]. The above characteristics significantly enhance the shear strength and energy absorption efficiency of the material [11], so that it can more effectively suppress shear failure and efficiently dissipate seismic input energy under ground motion.

(3) Large deformation characteristics under constant resistance : Another significant feature of NPR material is that it undergoes large-scale deformation under constant resistance. The static tensile test shows that NPR members (such as anchor cables) can continue to deform in the high constant resistance range of 200-900 kN, and the maximum deformation in the constant resistance stage can reach 2000 mm. The test shows that there is no yield platform in the whole tensile process of the material, and there is no typical necking phenomenon at the time of fracture, and the outstanding uniform deformation performance is always maintained [12[14]. In contrast, the deformation ability of traditional metal components has significant limitations.

(4) Impact resistance and fatigue resistance : After the traditional material is compressed at the impact point, its material usually flows along the direction perpendicular to the impact direction to the surrounding area. However, the negative Poisson 's ratio material shows a difference. When it bears the impact compression load, the side will shrink to the inside, prompting the material to gather to the impact center. Related studies have shown that NPR materials exhibit higher yield strength than traditional materials under the condition of consistent initial density [5,[9]. Under cyclic loading, the shear strength of NPR material remains stable [15]. The dislocation range of the upper and lower plates of the NPR steel anchorage structural plane under the pre-peak cyclic load is smaller, the fatigue damage deterioration degree of the joint surface is smaller, and the structural stability is higher. With the increase of the number of load cycles, the deflection angle difference between the NPR anchor and the PR anchor gradually increases [16], which further verifies the fatigue resistance of the NPR anchor. In the drop hammer impact test, the NPR material can effectively absorb the impact energy [17], thereby inhibiting the propagation of stress waves. For engineering structures that frequently suffer from earthquakes, this excellent energy dissipation capacity can significantly reduce the damage accumulation of the structure and prolong the service life of the structure.

2.2. Key Mechanical Mechanisms

The excellent performance of NPR materials is rooted in its unique mechanical mechanism. In terms of energy dissipation, the NPR anchor cable system composed of its core components (such as constant resistance body, constant resistance sleeve, steel strand and connector) generates high-frequency and high-amplitude seismic waves in the severe ground motion caused by earthquakes, which will be transmitted to the anchorage system in the form of stress waves. Once the stress wave amplitude exceeds the constant resistance threshold preset by the NPR anchor cable, a controllable displacement response will be generated between the constant resistance body and the constant resistance sleeve [18]. During the sliding process, the friction pair interface formed by the constant resistance body and the inner wall of the casing continues to produce stable friction. According to the principle of energy conservation, the kinetic energy and structural vibration energy input by seismic waves are continuously converted into friction heat and other forms of dissipation in this process. The comparison test shows that under the same conditions, the deformation damage degree and rock and soil crushing range of the slope supported by NPR anchor cable are significantly lower than those of the unsupported slope. By efficiently absorbing seismic energy, the NPR anchor cable can effectively reduce the peak acceleration of the slope and enhance its overall stability, thereby greatly reducing the degree of slope failure, fully verifying its excellent energy dissipation characteristics [18-19]. The failure of unsupported slope and NPR anchor cable supported slope is shown in Table 1.

Table 1. Failure comparison of unsupported slope and NPR anchor cable supported slope [18]

peak acceleration/($m{\cdot}s^{-2}$)	failure condition	
	Unsupported slope	NPR anchor cable supporting slope
5.0	Multiple tensile cracks appear on the slope surface, and local instability occurs.	There is only one tensile crack on the slope surface, and there is no local instability phenomenon.
6.0	The cracks on the slope continue to develop and interconnect with each other, and extend to the inside of the slope.	The crack development degree is low, and only occurs on the surface of the slope, does not extend to the inside of the slope, and there is no local collapse phenomenon in the slope.
8.0	The internal cracks are developed and connected locally, resulting in a connected sliding surface with a crack width of about 7 mm. The rock and soil on the sliding surface are separated from the slope and become dangerous rock mass.	A connected sliding surface with a width of only 1-2mm is generated at the same position ; the sliding body above the sliding surface is not separated from the rock mass.
10.0	The slope collapses in a large area, and the damage at the top of the slope is the most serious. The rock and soil mass at the exposed position of the circular sliding surface is broken.	The cracks continue to develop, and the tension cracks on both sides run through, but there is no large-scale collapse phenomenon ; the slope has good integrity and the rock and soil body is not broken.

Deformation compatibility constitutes another core mechanical mechanism of negative Poisson 's ratio (NPR) materials. Taking NPR bolt (cable) support as an example, when the geotechnical engineering structure (such as roadway or slope) deforms, the supporting component can achieve a synergistic dynamic response with the surrounding rock. This characteristic can efficiently transform the deformation energy released by the surrounding rock into the strain energy stored inside the component through the elastic and plastic deformation of the component itself[7],20]. During the whole response process, thanks to its excellent mechanical stability, NPR material can continuously provide reliable constant support resistance, effectively delaying the initiation of surrounding rock cracks and inhibiting their expansion.

NPR materials also show significant advantages in shear mechanical properties. Microscopic experiments show that the shear strength of NPR bolt steel is much higher than that of traditional bolt steel, and its ability to resist transverse shear deformation is more than 2.5 times that of the latter [8]. It is worth noting that even at a high normal stress of 10 MPa, the residual shear strength continues to increase with the increase of the number of cyclic loadings[16]. During the shear action, the unique transverse expansion effect of NPR material (i.e., the thickening of the cross section during tension) will spontaneously form a self-reinforced dynamic constraint ring. This characteristic effectively prevents the occurrence of interface slip by increasing the normal stress of the interface[8] and strengthening the interlocking effect between particles[16], thus significantly improving the overall stability of the supporting structure.

3. The Application of NPR Material in Engineering

3.1. Rock and Soil Support and Slope Reinforcement

3.1.1. Slope Engineering

Taking a high and steep slope project in a mining area in southwest China as an example, this area is affected by seasonal precipitation and fault tectonic activity at the same time. Two main cracks (L01 deep 22 ~ 26 m, L08 total length 233 m) are developed at the trailing edge of the slope, showing a tension-shear composite failure mode, which constitutes a potential sliding surface. Field monitoring and physical model tests confirmed that the average pre-tightening force applied by the NPR anchor cable is about 300 KN, and its axial force maintains a steady upward trend under 150 days of continuous load, and finally stabilizes in the range of 290 ~ 375 KN for a long time, showing excellent compensation mechanical properties. In sharp contrast, under the same conditions, the traditional (PR) anchor cable appears sudden instability, and the axial force value fluctuates violently. The numerical simulation results further clarify its disaster control mechanism. When the water content of the weak interlayer increases to 15 % ~ 20 % due to rainfall infiltration, the horizontal displacement of the slope increases significantly to 18.5 ~ 21.9 cm, while the vertical displacement increases more sharply to 101.8 ~ 291.0 cm. Under this critical state, the NPR anchor cable effectively curbs the continuous development of displacement by strictly limiting the maximum shear stress increment to within 8.29 × 10 2 MPa, which significantly enhances the dynamic stability of the slope and reduces the risk of surrounding rock slip[21].

The shaking table test results further confirm that under the same test conditions, the crack width of the potential sliding surface of the slope supported by NPR anchor cable is effectively controlled in the range of 1 ~ 2 mm, which is much lower than the crack width of 7 mm of the unsupported slope, and the overall damage degree is significantly reduced. When a strong earthquake wave with a peak acceleration of 10 m / s 2 is input, the overall instability and collapse of the unsupported slope occur ; on the contrary, the NPR support system maintains the overall integrity of the slope by efficiently absorbing seismic input energy, only showing local fracture expansion, and no significant rock and soil fragmentation is observed. Although the cyclic action of the seismic inertia force causes the fatigue effect of the constant resistance structure, resulting in a decrease in the axial force of the anchor cable, its value eventually converges and stabilizes at a constant level (about 60 KN), indicating that the anchor cable can still provide effective support force. In addition, NPR support significantly weakens the peak acceleration amplification factor (PGA) recorded by each monitoring point of the slope[18], and effectively delays the penetration time of the sliding surface, which effectively verifies the significant effect of NPR anchor cable in inhibiting slope deformation and enhancing seismic performance.

3.1.2. Tunnel Seismic

In the tunnel seismic engineering, the NPR anchor cable significantly enhances the seismic toughness of the fault-crossing tunnel by relying on its ' constant resistance energy dissipation-large deformation coordination ' coupling mechanism. For such projects, the traditional anchor cable often breaks due to stress concentration (the axial force is instantaneously zeroed) ; in contrast, the NPR anchor cable can continuously provide support resistance and passively dissipate seismic input energy by means of the friction slip between the anchor body and the casing to ensure that the axial force is maintained within a safe range. Its unique negative Poisson 's ratio behavior (manifested as radial expansion of casing under tension) further strengthens the synergistic deformation ability of anchor cable-surrounding rock and optimizes the overall stability. The results of shaking table model test[19]show that after the application of NPR anchor cable, the acceleration response amplitude of tunnel structure decreases by 30 %-50 %, the dynamic earth pressure decreases significantly, the peak strain decreases by more than 40 %, and the axial force of anchor cable does not appear abrupt failure. The technical advantage is that the constant resistance value can be customized by changing the diameter of the casing / anchor body, and the initial support force can be adjusted by combining the nut preload. It has excellent adaptive control ability and can effectively deal with complex geological conditions such as fault fracture zone, high seismic intensity area and soft rock large deformation tunnel. see Table 2.

Table 2. Comparison of seismic performance advantages between ordinary anchor cable and NPR anchor cable [19]

contrast ratio	conventional anchor cable	NPR anchor cable
Destroy the threshold value	Collapsing during 0.4g earthquake	0.8g earthquake still remains structural integrity
Axial force stability	Suddenly drop to zero after the peak (fracture failure)	Continue to maintain constant resistance (no sudden failure)
surrounding rock control	Stress concentration leads to local failure	Uniform tensile, inhibit stress concentration
Adaptability of fault zone	Extremely high risk of failure (axial force exceeding 45N)	Stable operation (peak axial force 40N)

Aiming at the support engineering of deep buried soft rock tunnel (such as high ground stress and high fragmentation geological environment in Hengduan mountain area), the combined support strategy of long and short NPR anchor cable is implemented. In this scheme, the long anchor cable (10.3 m) is used to anchor the stable rock layer in depth, and the constant resistance reaction force with the design value of 350 KN is provided. At the same time, the short anchor cable (6.3 m) is used to encrypt and reinforce the shallow broken surrounding rock, which effectively suppresses the local deformation. The ' point-line-surface ' three-dimensional collaborative support system is constructed through the connection of W steel strip and flexible network, and the synergy of long and short anchor cables. The engineering monitoring shows that after the application of the system[22], the axial force of the anchor cable is stabilized at 340 KN, the convergence settlement value of the surrounding rock is less than or equal to 170 mm, and the comprehensive deformation is controlled within 300 mm. The support efficiency is significantly improved compared with the traditional anchor cable scheme, reaching more than 3 times.

3.2. Seismic Reinforcement of Building Structure

The application of NPR steel-UHPC composite technology in structural seismic reinforcement shows excellent mechanical properties. Compared with ordinary HRB400 reinforced beams (brittle fracture is easy to occur under low reinforcement ratio, and only 1-2 main cracks are usually formed), UHPC beams with NPR steel bars can form about 8 uniform distribution of main cracks under bending load, which significantly improves the failure mode of traditional beams dominated by single main cracks. Under the same reinforcement ratio, the ultimate bearing capacity of beams with NPR steel bars is significantly better than that of ordinary steel beams, and the ultimate deflection increases by more than 50 %. The unique negative Poisson 's ratio effect (volume expansion characteristic) of NPR steel bar endows it with excellent stress transfer and distribution ability, which effectively disperses the deformation at the crack and reduces the risk of crack localization. Therefore, under the same load, the maximum crack width of NPR-UHPC beam is smaller, the crack distribution range is wider, and the expansion of crack height and width is also effectively suppressed[7]. This material combination breaks through the limitation of ' bearing capacity and ductility are difficult to take into account ' in traditional design, so that the beam has high bearing capacity and high ductility at the same time, and efficient seismic energy dissipation is realized. By dispersing the crack development path and delaying the structural damage process, this technology significantly enhances the seismic resilience of building structures and provides an innovative technical path for high-performance structures, especially for seismic scenarios.

For important building structures, NPR anchor cable reinforcement technology and G2-MBLSTM monitoring and early warning method can be integrated to build an intelligent disaster risk prevention and control system and realize real-time early warning of risks. In the specific implementation, high-precision wireless sensor networks are densely deployed at the key nodes of the building wall and the underground infrastructure according to the optimization scheme. The network continuously collects structural stress state, deformation displacement and potential geological disaster information. In order to solve the problem of long-term power supply, the hybrid energy harvesting technology is innovatively introduced. By collecting environmental vibration energy, radio frequency electromagnetic wave energy and soil temperature difference energy, the self-powered operation of the sensor is realized to ensure the continuity and accuracy of data acquisition[23].

3.3. Isolation Barrier and Metamaterial Design

The local resonance isolation barrier based on the negative Poisson 's ratio (NPR) material forms a synergistic double isolation mechanism by integrating the periodic local resonance unit with the NPR matrix. The experimental results show that the effective isolation frequency band (0.612-13.35 Hz) accurately covers the typical earthquake damage spectrum (0.5-12 Hz), and the peak vibration reduction efficiency is 74 %. In the low frequency region (0.612-3 Hz), the system uses the unique negative Poisson 's ratio characteristics of NPR materials to induce microstructure deformation and enhance local resonance energy dissipation. For the high frequency component (3-13.35 Hz), the band gap effect (due to Bragg scattering) generated by the periodic structure array is mainly relied on to block the elastic wave propagation path. The optimization study shows that[24] : when the angle of the support column is 60 °, the isolation frequency band can be optimized to 0.86-11.34 Hz, and the vibration reduction rate is increased to 92 % ; in addition, the selection of materials with smaller Poisson 's ratio, density and elastic modulus can significantly improve the overall performance (the specific parameter threshold needs to be determined in combination with engineering practice). This technology provides a new idea for seismic protection of critical infrastructure, but its engineering application needs to carefully weigh the cost input and actual benefits of NPR materials.

4. Experimental and Numerical Verification of Seismic Performance

4.1. Seismic Performance Test

4.1.1. Static and Dynamic Tensile Test

In order to evaluate the performance of negative Poisson 's ratio (NPR) materials in seismic and large deformation control, a systematic experimental study was carried out based on static and dynamic tensile test methods. The quasi-static loading method (displacement rate controlled at 0.1-1 mm / s) was used in the test. At the same time, combined with digital image correlation (DIC) full-field strain measurement technology and infrared thermal imaging monitoring, the load-displacement response characteristics and energy absorption process of NPR bolt were quantitatively analyzed. The test results show that[13,[],[25] :

(1) Constant resistance characteristics : The micro NPR bolt shows a significant horizontal platform characteristic in the constant resistance stage. The constant resistance is stable at 222.3 KN (fluctuation range < 10 %), the ultimate elongation exceeds 30 %, and the fracture surface has no necking phenomenon [17] ;

(2) Microscopic mechanism : dislocation-induced twin structure effectively suppresses local strain concentration and achieves uniform deformation, with energy absorption value of 61.22 kJ[25].

(3) Engineering practice verification : the measured ultimate pull-out force of Qingdao subway project reaches 253 KN, and the convergence of surrounding rock of Muzhailing tunnel is stably controlled within 200 mm[13]. These field data fully confirm that the constant resistance behavior of the material can effectively adapt to the dynamic disturbance environment of surrounding rock, and provide a reliable technical solution for large deformation control and rock burst protection under deep high stress conditions.

4.1.2. Cyclic Shear Test

The pre-peak cyclic shear test focuses on the fatigue damage characteristics and mechanical response of the micro-negative Poisson 's ratio (2G-NPR) anchor structural plane under cyclic loading below the ultimate shear strength. The test results reveal that :

(1) Shear strength strengthening effect : Under the condition of high normal stress (10 MPa), the peak shear strength of 2G-NPR anchorage structural plane continues to increase by 16.3 % with the number of cycles (50 → 200), showing significant fatigue resistance. However, the strength of the traditional Q235 PR steel anchorage structure plane decreases by 24.5 % under the same conditions [16] ;

(2) Advantages of dynamic load performance : When the cyclic loading rate increases from 1.0 KN / s to 1.5 KN / s, the shear strength of the 2G-NPR anchorage surface increases by 30 %, and forms a reverse response with the unanchored structural surface (strength decreases by 15 %) [15] ;

(3) Improvement of failure mode : when the cyclic amplitude increases from 50 % to 80 % of the ultimate stress, the strength of the 2G-NPR anchorage surface increases inversely, which effectively suppresses the brittle failure characteristics of the unanchored structural plane [15] ;

(4) Energy dissipation mechanism : The total absorption energy of the 2G-NPR anchorage system increases exponentially with the normal stress and the number of cycles (up to 2 times of the PR anchor at 200 cycles), and the microscopic negative Poisson 's ratio effect improves the toughness of the system by inhibiting stress concentration [16] ;

(5) Mechanical response optimization : The experimental data show that [16], compared with the traditional PR anchor, the shear stress-axial force ratio of the 2G-NPR anchor is always maintained at a lower level (the maximum difference is 1.62), which verifies the significant advantages of its axial bearing performance.

The above results confirm that the 2G-NPR bolt successfully overcomes the fatigue failure limit of traditional materials under pre-peak cyclic load conditions (typical such as open-pit mine blasting disturbance [15]) through unique dynamic strengthening effect.

4.1.3. Shaking Table Model Test

Based on the layered and compacted surrounding rock physical model (using gypsum / barite powder / river sand composite material to simulate IV / V grade surrounding rock) and precise fault dip control technology (wood separation + layered filling process), the shaking table test systematically verifies the performance of NPR anchor cable through the following methods [19] :

1.Load input : applying three-way Wenchuan wave (X / Y / Z acceleration amplitude ratio 1 : 0.7 : 0.9), loading along the transverse main shock direction of the tunnel (0.1g ~ 1.0g) ;

2.Model construction : Establish a 40 : 1 scale tunnel model (5mm polystyrene foam board is laid on the boundary to suppress the boundary effect) ;

3.Support control : 3D printed NPR anchor cable group (sleeve-anchor body friction constant resistance design) was compared with ordinary anchor cable group ;

construction of monitoring system : 90 high-precision sensors are deployed in the whole region to collect multi-parameter dynamic response data such as acceleration, strain, earth pressure and anchor cable axial force in real time.

The test results show that[19] under the action of 0.8g strong earthquake, the NPR support system significantly reduces the peak acceleration of the fault section by 33 % (1.0g vs 1.5g) compared with the ordinary anchor cable system, and the strain concentration of the spandrel is alleviated by 43 % (356με vs 623με). At the same time, the axial force of the anchor cable is stably maintained at a constant resistance state of 40 KN through the friction energy dissipation mechanism, which effectively prevents fracture damage. The post-earthquake deformation monitoring shows that only 4 mm controllable slip is generated in the NPR support area. The above results fully verify that the technology can efficiently attenuate seismic energy propagation through friction energy dissipation, and provide key technical support for seismic design of tunnels in strong earthquake areas.

4.2. Numerical Simulation

Numerical simulation plays a key role in analyzing the mechanical properties of negative Poisson 's ratio (NPR) materials. Based on the finite element analysis platforms such as ABAQUS and LS-DYNA, the researchers successfully realized the accurate parameter calibration and model embedding of the microscopic NPR bolt constitutive relationship, and effectively reproduced its mechanical behavior under quasi-static tension, multi-axial stress state and impact load[25]. The ABAQUS simulation results clearly show that the calibrated constitutive model can accurately predict the corresponding relationship between load and displacement in the whole process of quasi-static tension of anchor rod, and the obtained curve is highly consistent with the experimental data, which proves that the model has good reliability.

Numerical simulation technology can effectively reveal the key mechanism of material microscopic characteristics (such as rib structure) on macroscopic deformation behavior. The LS-DYNA simulation case proves that the unique thread rib design of NPR steel bar can disperse the stress concentration area during the tensile process and promote the development of more uniform plastic deformation. Compared with the plain steel bar, the necking expansion area is significantly increased, and shows a higher ultimate elongation[12]. This finding lays a theoretical foundation for optimizing the geometric configuration of NPR bolt and improving the energy absorption efficiency of large deformation. In particular, it should be noted that the numerical simulation results are in good agreement with the physical experiments. The research shows that[25], under quasi-static tensile conditions, the finite element calculation results based on the calibrated constitutive model are highly matched with the measured load-displacement curve. These advantages make numerical simulation become the core technical means to guide the design optimization and performance prediction of NPR materials.

5. Engineering Case and Effectiveness Analysis

Engineering cases and effectiveness analysis are shown in Table 3.

Table 3. Engineering case and effectiveness analysis

Engineering scene	Application form	Anti-seismic effect
Open-pit mine slope	NPR anchor cable	The horizontal displacement is reduced by 50 %, and the rainfall-induced sliding is inhibited[21,26].
Tunnel through fault	NPR anchor cable support system	The seismic damage is reduced, and the axial force has no sudden drop[19].
Deep buried soft rock tunnel	Long and short NPR anchor cable combination	Surrounding rock convergence < 300mm[22] .
.Important buildings	NPR anchor cable + G2-MBLSTM	Real-time monitoring and early warning, structural deformation controllable[23] .
UHPC beam	NPR rebar	Crack dispersion, ductility improvement[7] .

6. Existing Problems

NPR materials exhibit significant mechanical property degradation at high temperatures (especially ≥ 400 ° C). Studies have shown that [27], its ultimate strength, yield strength and elastic modulus decrease sharply with the increase of temperature (such as the strength at 800 ° C is only 20 % of room temperature), and the fracture characteristics change from toughness to brittleness. This deterioration is due to material oxidation (the increase of oxygen content and the decrease of iron content) and the unique ' blue brittleness effect ' in the range of 400-600 ° C, resulting in ductility loss, which seriously weakens its application reliability and safety in tunnel fire, high temperature industry and other scenarios.

Under cyclic or dynamic loads (such as earthquakes), the NPR anchorage system faces the problem of constant support resistance attenuation. Experiments have confirmed that [18] : repeated inertia force will induce the fatigue effect of constant resistance structure, so that the constant resistance continues to decrease and stabilize below the initial design value. Although there is still residual support force, its anti-deformation and energy absorption capacity are significantly weakened. The research on key parameters such as fatigue life and crack evolution mechanism of microscopic NPR steel under cyclic loading is still blank[13], which constitutes a potential risk for power engineering applications.

NPR materials (especially microscopic NPR steel) have the limitations of complex preparation process and high cost. Micro NPR steel requires special alloy ratio (such as specific Mn / Cr content) and multi-scale coherent interface smelting process to achieve high strength and toughness without necking. Macroscopic NPR anchor cables rely on precision constant resistance components (such as stainless steel constant resistance bodies and 3D printed resin sleeves) [18], which have strict requirements on manufacturing and assembly accuracy. At present, the application is limited to demonstration projects, and a large-scale industrial chain has not yet been formed [13], which restricts its cost optimization and engineering promotion potential.

7. Conclusion

Based on its inherent negative Poisson 's ratio characteristics and constant resistance large deformation mechanism, NPR material provides an innovative technical path for improving the seismic toughness of engineering structures with its excellent energy absorption efficiency.

Shaking table test, numerical simulation and engineering practice verify that the material shows significant performance advantages in slope stability control, tunnel support system, building structure reinforcement and isolation barrier, which can efficiently dissipate seismic energy, coordinate structural large deformation response and reduce dynamic load effect. However, its high temperature sensitivity, fatigue degradation induced by cyclic loading (such as constant resistance attenuation) and high cost preparation process are still the key bottlenecks restricting large-scale engineering applications. Future research should focus on the above problems to promote the wide application of NPR materials in the disaster prevention system of major projects.

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