Numerical simulation of coal samples creep properties under graded loading conditions

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Abstract

To study the creep characteristics of coal samples under graded loading conditions, on the basis of the physical experiments, using FLAC3D software to numerical simulated the coal samples from different angles. The numerical simulation results show that the simulation results match with the physical experimental results in both strain magnitude or the general tendency of creep, which verifies the correctness and applicability of the customized numerical simulation model. Based on the above results, further research can be conducted that the coal creep characteristics under different conditions. It is found that the transverse strain magnitude at the top of the specimen is more obvious than bottom, which shows the process of stress transfer from top to bottom; the bulk modulus has less influence on the creep of specimen, and the creep of specimen decreases with the increase of bulk modulus under the same conditions; the shape has a great influence on the creep of specimen, the cylindrical specimen creep is much larger than the rectangular specimen creep under the same conditions; when the height of specimen increases, not only the creep magnitude increase of specimen, but also the creep degree of gradually increase. Hence, the conclusions attained can provide a good guidance to the analyse the creep of coal.

1 Introduction

Rock creep is defined as the phenomenon of growing rock deformation with time under constant stress conditions(Hu et al. 2015). Coal is essentially a rock, and the creep of coal essential is a creep of rock. It is because the creep of rock is closely related to stress and time ,it is difficult to completely simulate the long time and constantly changing stress of rock in the actual experiment process. Therefore, by numerically simulating the creep of rocks and using software to simulate the rock creep characteristics at different times and under different stresses, the above-mentioned difficulties can be effectively solved.

In 1939, Griggs found that creep occurred when the load reached 12.5% to 80% of the breaking load during creep tests(David 1939). In recent years, different scholars put forward improved models based on the classical creep model(Sun et al. 2021; Chen et al. 2021; Cheng et al. 2021; Wang et al. 2021; Li et al. 2020; Su et al. 2018; Yang et al. 2017; Qi et al. 2012). By carrying out rock tests of uniaxial compression, triaxial compression, and cyclic loading, the academia has further understanding of the creep characteristics and influencing factors of rock under different conditions(Liu et al. 2020; Zhang et al. 2020; WU et al.2020; Zhao et al. 2018; Yang et al. 2017; Su et al. 2014; Yang et al. 2014; Lu et al. 2011;Chen et al. 2009; V. L. et al. 2005) .

For the creep of coal, Xiao Fukun pointed out that the coal body exhibits different creep characteristics under different constant stresses(Xiao et al.2020) . Guangzhi Yin described the three stages of coal rock creep using the traditional Nishihara model and determined the relevant parameters(Yin et al. 2008). Based on the uniaxial compression creep results, Liu Zheng pointed out that the stable creep stage accounted for the largest proportion of the whole creep curve(Liu 2012). Ding Zeng proved that the Burgers model can fit the creep curve of coal samples, and numerically simulated the creep process of the roadway envelope rock based on Flac3D software(Ding 2021). Duan Huiqiang conducted a graded loading creep test on coal samples, analyzed the effect of different stress levels on the creep process produced by coal samples(Duan 2021). Li Xiangchun studied the creep properties of gas-bearing coal samples and proposed a mathematical relationship between creep and seepage rate(Li et al. 2018). He Feng determined the creep properties of coal rocks with different water contents, pointed out the effect of water content variation on creep of coal rocks(He et al. 2011). Wang Dengke used power and exponential functions to describe the creep rates of decelerating creep stage and stable creep stage of gas-bearing coal samples(Wang et al. 2010).

In terms of numerical simulation of rock creep, Gao Wenhua conducted numerical simulation of uniaxial compression of siltstone, to explore the creep properties of siltstone at different stress levels(Gao et al. 2015); Zhang Zhipei studied the rheological properties of soft rock masses under different surrounding pressure states, and the effects of different forms of specimens in indoor tests through numerical simulation(Zhang et al. 2011); Wang Yong-yan simulated creep of similar materials in soft rock , proved to be basically consistent with those of soft rock[32]; Wu Yang used ABAQUS analysis software to simulate the creep characteristics of tunnel surrounding rock in cold regions(Wang et al. 2018); Wang Jun-guang established PFC2D model to perform indoor creep tests and numerical simulations under different loading and unloading conditions(Wang et al. 2019); Tian Wenling analyzed the samples parameters and crack expansion process of coal samples under different surrounding pressures based on simulation tests(Tian et al. 2015); Lu Yinlong studied the creep characteristics of rocks at three stages through simulation, and pointed out the whole process of rocks from mesoscopic aging damage to macroscopic fracture(Lu et al. 2015); Li Lianchong established the RFPA2D numerical model and applied it to simulate the creep damage process of rocks under constant load(Li et al. 2007); Xiao Huajie proposed the idea of segmental simulation to study the transient and creep strains , thus established a creep intrinsic model for simulation(Xiao et al. 2020).

It can be found that there are many research results on the numerical simulation of creep of coal and rock creep, but few scholars have combined the two research, to numerically simulate the creep of coal. Therefore, we by conducting uniaxial compression experiments on coal samples, studying their creep characteristics under graded loading conditions, comparing and analyzing them, selecting a suitable intrinsic model, using Fish language to written the program of custom numerical simulation model.Based on FLAC3D software, numerical simulations of creep tests were carried out, and creep properties of coal samples under different conditions were further simulated.

2 Experiment System And Plan

2.1 Experiment system

As shown in fig1(a), the experiments were carried out using Tenson testing machine for loading of axial compression. Different stress loading methods and conditions can be imposed using the press operation software TensonTest, and displacement control is used in uniaxial compression loading.

Micro-Measurements-7000 strain tester and StrainSmart of data acquisition software were used to complete the uniaxial loading stress-strain data acquisition. The monitoring system is shown in fig1(b).

2.2 Experiment plan

Considering the discrete nature of the raw coal properties due to the non-homogeneity of the coal seam, in order to unify the test variables and better highlight the test results, the required samples are all from the Sihe mine in Qinshui County, Jincheng City, and the size of the specimens used is 50mm×50mm.The coal sample is shown in fig1(c).

Uniaxial compression experiments were performed on the coal samples, to obtain the strengths of the coal samples under uniaxial compression conditions, and this was used as a basis for constructing the intrinsic model for numerical simulation of the coal samples. After obtaining the strength of coal samples, the coal samples were graded for uniaxial compression. The loading was performed in stress-controlled loading mode with a loading rate of 0.5 MPa/s. When the stress level reached 3.25 MPa, 5.9 MPa, 8.85 MPa, 11.8 MPa, 14.75 MPa, and 17.7 MPa, each coal sample was loaded in a graded manner, and each level of loading lasted 300s until the specimen ruptured. During the test, 10 kHz frequency was selected for measurement, and the stress and strain data were collected in real time, the loading was controlled by the program.

3 Experiment Result

3.1 Uniaxial compression result

The obtained stress-strain curves are shown in fig2(a). From the figure, it can be seen that there is a strong correspondence between the axial strain, transverse strain and stress curve. The stress curve increases first and decreases instantaneously after complete rupture occurs. The damage strength of this loading is 11.6 MPa obtained from the stress curve and servo machine data.

When the stress value is rising, the axial strain value is decreasing and the axial strain value is negative, indicating that the coal sample is in compression and the strain accumulation is increasing; until after the rupture occurs, the strain value increases instantaneously and the axial strain value is at the lowest value of the graph line at the time of rupture, when the strain of the specimen is most obvious.

There is a strong correspondence between the changes of transverse strain and axial strain. When the stress value is rising, the transverse strain value is also rising, the transverse strain value is positive, and the strain accumulation is increasing; until the rupture occurs, the strain value decreases instantaneously, and the transverse strain value at the time of rupture is at the highest value of the graph line, when the strain of the specimen is most obvious.

3.2 Graded loading results

As can be seen from fig2(b), before the creep stress reaches the breaking strength of the coal sample (the first to sixth creep stress), the creep of the coal sample shows two stages of initial decay creep and stable creep in the axial direction. Before the creep stress reaches the breaking strength of the coal sample, the axial strain increases in gradient with increasing of stress . When the creep stress reaches the destruction of coal sample, the creep of coal sample in the axial direction is in three stages of initial decay creep, stable creep and accelerated creep. After the creep stress reaches the breaking strength, the creep rate increases very fast, accelerated creep occurs, and the coal sample ruptures.

strain of the coal sample have the same pattern in the first to fifth stress. At the first to fifth stress of creep in coal samples, the creep of coal samples showed two stages of initial decay creep and stable creep in the transverse direction. The gradient of transverse strain increases with the increase of stress. However, when the sixth stress level was applied, the creep of coal sample showed three stages of initial decay creep, stable creep and accelerated creep in the transverse direction.

It is noteworthy that the stress of coal sample creep in axial and transverse strains into the accelerated creep stage are different, and the rupture of coal sample in transverse direction is earlier than that in axial direction.

4 Creep Model

4.1 Constitutive model

The simulation is performed using FLAC3D, a simulation software developed by ITASCA (USA). FLAC3D uses a hybrid discrete partitioning technique of explicit and Lagrangian algorithms to simulate plastic damage and flow of materials very accurately. The software itself has a variety of embedded material models that can be used to simulate the post-force properties of coal samples. FLAC3D uses the Fish language to write creep models based on its embedded intrinsic model, and invokes the program for numerical simulation.

In FLAC3D, the commonly used models for simulating creep are Maxwell model and Burgers model.The Maxwell model is composed of an elastic element in series with a viscous element, and its mechanical model is shown in Fig3(a)(Cao 2019).

Its creep equation is $\varepsilon(\mathrm{t})=\frac{\sigma}{\eta}\mathrm{t}+\frac{\sigma}{E}$

A typical Burgers model is composed of a Maxwell model and a Kelvin model in series, and its mechanical model combination is shown in fig3(b)(Kang et al. 2011).

Burgers creep equation is $$\varepsilon = \frac{\sigma_0}{E_1} + \frac{\sigma_0}{\eta_1} + \frac{\sigma_0}{E_2}\left(1 - e^{-\frac{E_2}{\eta_2}t}\right)$$

To obtain accurate simulations, creep models with Maxwell model and Burgers model were established and simulated at the first level of stress, respectively, and the simulation results are shown in Fig4.

It can be seen from the figure that the instantaneous creep of Burgers model is larger than the instantaneous creep of Maxwell model, and although the magnitude of axial strain in the stable creep stage is the same for both, Burgers model enters the stable creep stage earlier, which is also more consistent with the results of actual experiments. Therefore, the Burgers model was used to construct the creep model for numerical simulation.

4.2 Creep model construction

The uniaxial creep model was established based on the burgers intrinsic structure model, which has 1111 nodes and 1000 cells. After the model is established, the same stress as the experiment is applied in the Y-direction , keep the same magnitude of stress as in the actual experiment. And no stress is applied in other directions, to ensure the accuracy of the simulation. Node A(0,0,0) is selected on the model to detect axial displacement. Node B(-0.025,0,0) and node C(-0.025,0.099,0) are selected on the model to monitor their lateral displacements. Fig5 shows the schematic diagram of the numerical simulation of the first level stress under uniaxial conditions.

5 Numerical Simulation Analysis

5.1 Comparison of simulation results

The coal sample parameters have been obtained by uniaxial compression, and the parameters are imported into the model that established by FLAC3D, and the numerical simulation is started. According to the results of numerical simulation under different stress, the axial strain value of monitoring point A is derived. The axial creep curve of monitoring point A is plotted, and the numerical simulation curve under different stresses is compared with the creep experimental curve, as shown in fig6.

From the fig6, it can be seen that the experimental results are extremely similar to the numerical simulation results, whether it is the axial strain values and the trend of the axial creep curve. This also proved the rightness of the established model, and laid the foundation for the next step that analyzing the effect of different parameters on coal creep. From the stage of creep, the deformation appears at the moment of stress loading, and after the decay creep and isometric creep into the stable creep stage. However, analyzing the overall creep curve, the difference between the experimental and simulated curves appears in the initial creep stage, which is especially obvious when the stress is small, which will be discussed in the following.

5.2 Comparison of transverse creep at different locations

After the previous paper verified the rightness of the model built based on Fish language to simulate creep in FLAC3D software, the following section analyzes the effect that different parameters on the creep characteristics of coal samples through numerical simulations.

At the third level of stress , the transverse strain values are derived for point B and point C. B is located at the top of the model ,and C is located at the bottom of the model. The transverse creep curves of monitoring points B and C are plotted, and the transverse creep comparison is shown in Fig7(a).

As can be seen from Fig7(a), at different locations of the specimen in the vertical direction, they have different strains, and the top transverse strains of the specimen greater than the bottom. The instantaneous strain values at the top is 211, and the bottom is 194, the former was 1.08 times of the latter. The creep values from the top to the bottom of the specimen showed a decreasing trend, which reflected a transfer process that stress from the top to the bottom. So, in terms of transverse creep, the top was more affected by the stress and more prone to deformation.

5.3 influence of different bulk modulus on creep

According to the common rock mechanical parameters, the numerical simulations were set at the conditions of bulk modulus of 0.25 Gpa, 0.35 Gpa and 0.45 Gpa. A third level of stress is applied to the model, andthe axial displacement at point A (0, 0, 0) is monitored, and the creep simulation curves are shown in Fig7(b).

From Fig7(b), it can be seen that when the parameter of bulk modulus changes, the instantaneous strain and creep of the coal sample also change. When bulk modulus is 0.25Gpa, the instantaneous strain values is -56; when bulk modulus is 0.35, the instantaneous strain values is -72; when bulk modulus is 0.45Gpa, the instantaneous strain values is -101. It can be seen that the bulk modulus has a greater influence on the creep of coal samples, and the creep of coal samples decreases with the increase of bulk modulus. But , the coal samples with different bulk modulus have the same time from deceleration creep to steady creep, and their creep simulation curves have the same time to fluctuate. However, whether there is a linear relationship between the change of bulk modulus and creep of coal samples needs to be further investigated.

5.4 Influence of different shapes on creep

Set rectangular coal sample model with X=50mm,Y=100mm,Z=50mm , and all other data are the same as the cylindrical model established above. The third level of stress is applied to the model, and the displacement in the axial direction at point A (0, 0, 0) is still monitored. The creep is compared with that of the cylindrical coal sample, and the creep simulation curve is shown in Fig7(c) below.

From Fig.7(c), it can be seen that the instantaneous creep value of the cylindrical coal sample is -685; the instantaneous creep value of the rectangular coal sample is -423. The creep value of the cylindrical coal sample is much larger than the rectangular coal sample, and the former is 1.62 times of the latter, which indicates that the rectangular coal sample is more stable and can bear greater stress under the same conditions.

5.5 influence of specimen height on creep

To study the influence of specimen height on creep, the cylindrical specimens with heights of 95 mm, 100 mm, 105 mm and 110 mm were simulated numerically, applied the third level of stress and the displacement in the axial direction was monitored at point A (0, 0, 0). The creep simulation curves are shown in Fig7(d).

From Fig7(d), it can be seen that the axial strains produced by specimens of different heights are not the same under the same stress. When the height increases, the instantaneous creep value at point A increases accordingly. When the height is 90mm, the instantaneous creep value at point A is -666, when the height is 100mm, the instantaneous creep value at point A is -686, the latter is 1.03 times of the former; when the height is 100mm, the instantaneous creep value at point A is -686, when the height is 105mm, the instantaneous creep value at point A is -722, the latter is 1.05 times of the former; when the height is 105mm, the instantaneous creep value of point A is -722, and when the height is 110mm, the instantaneous creep value of point A is -842, the latter is 1.16 times of the former. The above three ratios are getting bigger, so the creep ratio of the same height difference also increases when the height of the model increases continuously. It can be seen that the change of the model height has a significant influence on the creep, and the creep increases with the increase of the model height, and the degree of creep is also increasing.

6 Discussion

From Fig6, it can be seen that the creep experimental curve and the creep simulation curve have extremely similar trends that strain values and creep, during the stable creep stage at different stress. However, in the overall creep curve, the creep curve has a larger deformation at the instant of loading, the creep experimental curve has a larger difference with the creep simulation curve, which is especially obvious at the first level of stress and the second level of stress. Through analysis, it is found that when carrying out experimental loading, each level of stress loading will produce large fluctuations at the beginning, and the stress fluctuations will only gradually stabilize after a period of time, and finally maintain near the set stress magnitude, as shown in Fig2(b). But FLAC3D in the simulation, different levels of stress loading can be stable loading to the next level, the stress does not produce large fluctuations. Therefore, the creep curve produced by the numerical simulation is smoother, which also leads to the difference between the creep experimental curve and the creep simulation curve at the moment of loading, and the creep experiment curve fluctuates time at different stress levels coincides with the stress fluctuates at stress loading time. Since the stress applied at the first stress level and the second stress level is smaller, the creep of the coal sample is smaller than the other stress levels, and in the case of stress fluctuations, the same stress difference will have a greater effect on the creep curve at that stress level.

It has been previously mentioned in the paper, the numerical simulations can simulate similar results to the experimental results in terms of the magnitude of each phase of creep, there are differences in the degree of sensitivity to changes in axial and transverse strains. The trends and strain values of transverse creep are both less pronounced in numerical simulations than axial creep(Gao et al. 2015). Our experiments also confirmed this view. The influence of different physical properties on the creep of coal samples was tested by changing the relevant physical properties in numerical simulations, and the results obtained were verified with other paper results(Cao 2019), Further proof that the influence of physical properties on the creep of coal samples.

When simulations were performed, it was found that the creep produced by graded loading was not the same as that produced by applying a constant stress at the same stress, as shown in Fig7(c) for cylindrical specimens with different creep than that of the third level of stress in Fig6(c). It was analyzed that the coal samples showed damage during graded loading and their elastic modulus varied linearly at the loading stages with different stresses(Duan et al. 2021), which influenced the creep of the samples. In the actual production process, it is difficult to know the variation of past stress loading of coal rocks, and the analysis of creep only under current stress loading conditions, may deviate from the actual situation. This also reveals the next research direction to further analyze, the law of elastic modulus change for the coal after damage during graded loading. Based on the analysis of the law of elastic modulus change, the model is improved so that the creep simulation of coal samples under constant stress conditions further approximates the creep under graded loading conditions.

7 Conclusion

In this paper, uniaxial compression experiments and graded loading experiments were carried out on coal samples from the Sihe mine in Qinshui County, Jincheng City, as the research object. The basic physical properties were obtained through the experiments, and the Burgers model was used to establish the model based on Fish language in accordance with the experimental coal samples, which was embedded in FLAC3D to numerically simulate the creep properties under the graded loading conditions. The following conclusions were obtained:

(1) FLAC3D can be used to build a model and carry out numerical simulation, and the simulated data obtained are basically consistent with the experimental data. This proves the correctness and applicability of the model.

(2) By comparing the creep experimental curves with the creep simulation curves, the correctness of the burgers model, which comes with FLAC3D software. This fully proves that under the condition of knowing the basic physical characteristics of the coal, FLAC3D software can be used for numerical simulation of creep of different coal, and can be obtain accurate results.

(3) By monitoring the nodes at different positions, it was found that the creep at the top of the coal sample was more obvious than the bottom, reflecting the transfer process of stress from top to bottom. Through numerical simulation of models with different shapes, different bulk modulus and different heights, it was found that the influence of shape on creep of coal samples, the creep of rectangular coal samples was significantly larger than cylindrical coal samples; and the influence of the change of bulk modulus on creep of coal samples was analyzed; comparing the creep caused by the change of height, it was found that the creep value and the degree both increased with the increase of height.

Declarations

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

Li. Xiangchun and Zhuo. Xuefei wrote the main manuscript text, Zhang. Liang and Yang. Tao did the experiment, Zhang. Kai and Bai. Shipeng and Zong. Chenghao and Wang. Yinqing and Xing. Mingxiu prepared figures. All authors reviewed the manuscript.

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Availability of data and materials

All data generated or analysed during this study are included in this published article.

References

1. Hu Bo, WANG Zong-lin, LIANG Bing, Li Gang, Wang Jun-guang, Chen Gong. Experimental Study of Rock Creep Properties [J]. Journal of Experimental mechanics, 2015,30(04):438-446
2. David Griggs. Creep of Rocks[J]. The Journal of Geology,1939,47(3):
3. Sun Xiao-ming, MIAO Cheng-yu, JIANG Ming, ZHANG Yong, Yang Liu, GUO Bo. Experimental and theoretical study on creep of sandstone with different water content based on improved Xiyuan model[J].Chinese Journal of Rock Mechanics and Engineering,2021,40(12):2411-2420.DOI:10.13722/j.cnki.jrme.2021.0302
4. Chen Guoqing, Wan Yi, Sun Xiang, Zhang Guangze. Creep characteristics and fractional damage model of sandstone after freezing-thawing with different temperature difference[J].Chinese Journal

of Rock Mechanics and Engineering,2021,40(10):1962-1975.DOI:10.13722/j.cnki.jrme.2021.0064

5. Cheng Hao,Zhang Yuchen,Zhou Xiaoping. Nonlinear Creep Model for Rocks Considering Damage Evolution Based on the Modified Nishihara Model[J]. International Journal of Geomechanics,2021,21(8):
6. Wan Yi, Chen Guoqing, Sun Xiang, Zhang Guangze. Triaxial creep characteristics and damage model of red sandstone with different moisture content after freezing-thawing[J].Chinese Journal of Geotechnical Engineering,2021,43(08):1463-1472
7. Li Dejian, Liu Jielin, Han Chao. Damage creep model of variable-order fractional rocks based on equivalent viscoelasticity[J].Rock and Soil Mechanics,2020,41(12):3831-3839.DOI:10.16285/j.rsm.2020.0419
8. Su Teng, ZHOU Hongwei, ZHAO Jiawei, CHE Jun, SUN Xiaotong, Wang Lei. Rock creep model based on fractional derivative of variable order[J].Chinese Journal of Rock Mechanics and Engineering,2019,38(07):1355-1363.DOI:10.13722/j.cnki.jrme.2018.1382
9. Yang Xiurong, Jiang Jiangnan, Jiang Zongbin. Creep test and damage model of soft rock under water bearing condition[J].Rock and Soil Mechanics,2018,39(S1):167-174.DOI:10.16285/j.rsm.2017.2560
10. Qi Yajing, Jiang Qinghui, Wang Zhijian, Zhou Chuangbing. Improved 3d creep constitutive equation and parameter identification of Nishihara model[J].Chinese Journal of Rock Mechanics and Engineering,2012,31(02):347-355
11. Liu Zhong-yu, DONG Xu, ZHANG Xu-yang. Experimental study on mechanical properties of coal under graded cyclic loading[J].Chinese Journal of Rock Mechanics and Engineering,2021,40(S1):2593-2602.DOI:10.13722/j.cnki.jrme.2020.0643
12. Zhang Peisen, ZHAO Chengye, LI Tenghui, Hou Ji-un, ZHANG Rui. Experimental study on wave velocity variation and energy evolution of red sandstone during triaxial loading[J].Chinese Journal of Rock Mechanics and Engineering,2021,40(07):1369-1382.DOI:10.13722/j.cnki.jrme.2020.1145
13. Li Wenzhou, SI Linpo, Lu Zhiguo, Yi Kang, Wu Longyun. Determination of crack initiation strength of coal under uniaxial compression and influence analysis of key factors[J/OL].Journal of China Coal Society:1-11[2022-01-10].DOI:10.13225/j.cnki.jccs.xr20.1872
14. Wu Fa-quan, QIAO Lei, GUAN Sheng-gong, ZHANG Qing-tong, WANG Zhao-yuan, Wu Jie. Study on size effect of small size rock samples under uniaxial compression test[J].Chinese Journal of Rock Mechanics and Engineering,2021,40(05):865-873.DOI:10.13722/j.cnki.jrme.2020.0555
15. Zhao Guo-kai, HU Yao-qing, JIN Pei-hua, HU Yue-fei, LI Chun, ZHU Xiao-zhou. Experimental study on uniaxial mechanical properties of granite under real-time temperature and cyclic loading[J].Chinese Journal of Rock Mechanics and Engineering,2019,38(05):927-937.DOI:10.13722/j.cnki.jrme.2018.1277
16. Yang Xiaobin, Han Xinxing, Liu Enlai, ZHANG Zipeng, WANG Tengjiao, ZHANG Lihui. Evolution characteristics of non-uniform deformation of rock under uniaxial cyclic loading and unloading[J].Journal of China Coal Society,2018,43(02):449-456.DOI:10.13225/j.cnki.jccs.2017.1119

17. Su Chengdong, Chen Xiaoxiang, Yuan Ruifu. Analysis of deformation and strength characteristics of coal samples under graded relaxation under uniaxial compression[J].Chinese Journal of Rock Mechanics and Engineering,2014,33(06):1135-1141.DOI:10.13722/j.cnki.jrme.2014.06.006
18. Yang Yong-jie, WANG De-chao, GUO Ming-fu, LI Bo. Damage characteristics of rock based on triaxial compression acoustic emission test[J].Chinese Journal of Rock Mechanics and Engineering,2014,33(01):98-104.DOI:10.13722/j.cnki.jrme.2014.01.008.
19. Lu Xinjing, Li Zhijing, Fang Houguo, Deng Weijie. Dominant size and size effect of rock uniaxial compressive strength[J].Yellow River,2011,33(04):107-109
20. Chen Wei-zhong, TAN Xian-jun, LU Sen-peng, Yang Jian-ping, WU Guo-jun, Yu Hong-dan, WANG Zheng-ming, ZHU Lin. Study on large scale triaxial compression rheological test and constitutive model of deep soft rock[J].Chinese Journal of Rock Mechanics and Engineering,2009,28(09):1735-1744
21. V. L. Shkuratnik,Yu. L. Filimonov,S. V. Kuchurin. Regularities of Acoustic Emission in Coal Samples under Triaxial Compression[J]. Journal of Mining Scinece,2005,41(1):
22. Xiao Fukun, Li Renhe, LI Lianchong, Hou Zhiyuan. Deformation and internal damage characteristics of coal under graded constant load[J].Journal of Heilongjiang University of Science and Technology,2020,30(01):1-7
23. Yin Guangzhi, ZHAO Hongbao, ZHANG Dongming. Triaxial creep characteristics and constitutive equation of outburst coal[J].Journal of Chongqing University,2008(08):946-950
24. Liu Zheng. Experimental study and numerical simulation on creep characteristics of deep surrounding rock[D].Hunan University Of Science and Technology, 2012
25. Ding Zeng, ZHANG Qi-ming, WANG En-yuan, FENG Xiao-jun, Chen Tao. Numerical simulation of influence of creep characteristics of deep surrounding rock on roadway stability[J].Chinese Journal of Underground Space and Engineering,2021,17(S1):404-410+432
26. Duan Huiqiang. Experimental study on creep failure of coal samples under graded loading[J].Safety in Coal Mines,2021,52(07):54-60.DOI:10.13347/j.cnki.mkaq.2021.07.009
27. Li Xiangchun, ZHANG Liang, Zhao Yiliang. Creep and seepage evolution of gassy coal under conventional triaxial pressure[J].Advanced Engineering Sciences,2018,50(04):55-62.DOI:10.15961/j.jsuese.201800099
28. He Feng, MENG Fanzun, Wang Zhenwei, Zhao Guo-chao. Experimental study on creep effect of water and coal rock[J].Journal of Liaoning Technical University(Natural Science),2011,30(02):175-177
29. Wang Dengke, Liu Jian, Yin Guangzhi, WEI Xiaoji. Experimental study on creep characteristics of coal sample containing gas under triaxial compression[J].Chinese Journal of Rock Mechanics and Engineering,2010,29(02):349-357
30. Gao Wenhua, LIU Zheng, Zhang Zhimin. Numerical simulation of compression creep test of siltstone based on FLAC~(3D)[J].China Civil Engineering Journal,2015,48(03):96-102.DOI:10.15951/j.tmgcxb.2015.03.014

31. Zhang Zhipei, Wang Zhiyin, Peng Hui. Triaxial compression creep test and numerical simulation of mudstone in southern Shaanxi[J].Hydrogeology & Engineering Geology,2011,38(01):53-58.DOI:10.16030/j.cnki.issn.1000-3665.2011.01.025.
32. Wang Yong-yan, Sun Min, GUO Peng, ZHANG Zuo-liang, ZHANG Yu-biao. Experimental study on creep characteristics and numerical simulation of similar model of soft rock[J].Coal Science and Technology,2018,46(10):125-129.DOI:10.13199/j.cnki.cst.2018.10.019
33. Wu Yang, He Qiangqiang, Wang Yongyan. Creep Characteristics of rock-like materials under freeze-thaw Cycles [J]. Industrial Construction,2020,50(10):106-110+62.DOI:10.13204/j.gyjzG20010110
34. Wang Jun-guang, Yang Peng-jin, LIANG Bing, Jin Qiao. Study on creep fracture law of mudstone under different loading and unloading conditions based on particle flow program[J].Journal of Experimental mechanics,2019,34(05):873-882
35. Tian Wenling, Yang Shengqi, Fang Gang. Particle flow simulation of mechanical characteristics of triaxial cyclic loading and unloading of coal samples[J].Journal of China Coal Society,2016,41(03):603-610.DOI:10.13225/j.cnki.jccs.2015.0505
36. Lu Yinlong, Wang Lianguo. Numerical simulation of creep damage and fracture process of rock based on microcrack evolution[J].Journal of China Coal Society,2015,40(06):1276-1283.DOI:10.13225/j.cnki.jccs.2014.3034
37. Li Lian-chong, Xu Tao, TANG Chun-an, ZHU Li-kai. Numerical simulation of rock creep instability failure process under uniaxial compression[J].Rock and Soil Mechanics,2007(09):1978-1982+1986.DOI:10.16285/j.rsm.2007.09.040
38. Xiao Huajie, Hu Peng, Zeng Caiyun, JIA Yi, WEI Jianbing. Test and subsection simulation of creep mechanical properties of unsaturated soils[J].Science Technology and Engineering,2020,20(22):9133-9139
39. Cao Li. Study on creep characteristics and creep model of coal with different coal structure[D].Anhui University of Science and Technology,2019
40. Kang Yonggang, Zhang Xiue. Unsteady creep model of rock based on Burgers model[J].Rock and Soil Mechanics,2011,32(S1):424-427.DOI:10.16285/j.rsm.2011.s1.050.

Figures

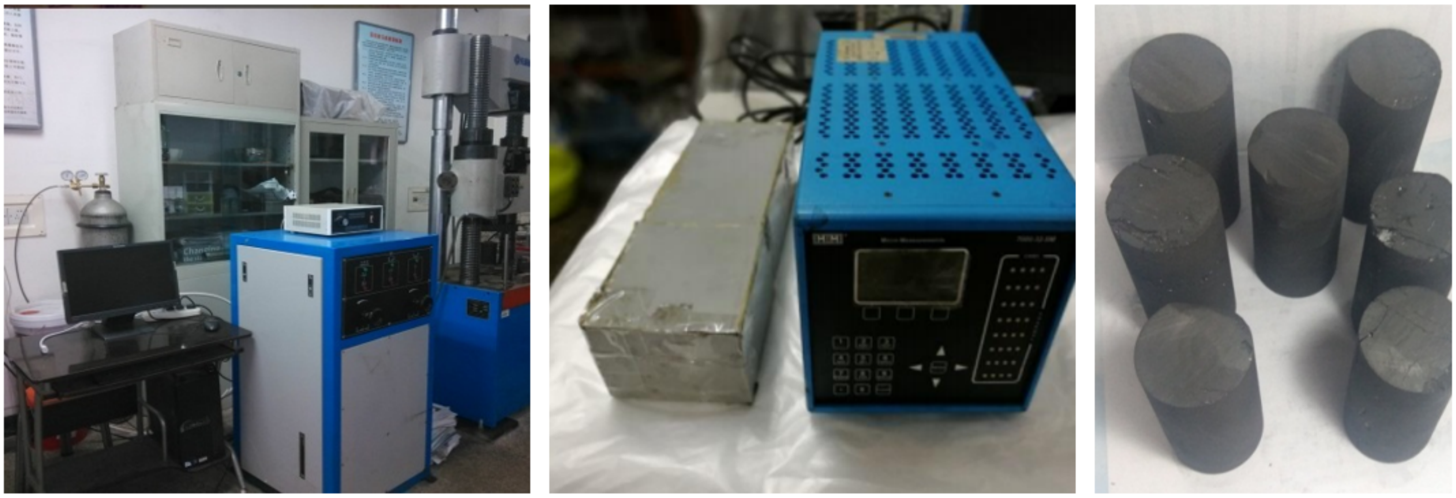

Figure 1

(a) Tianchen test machine

(b) Strain gauge

(c) coal sample

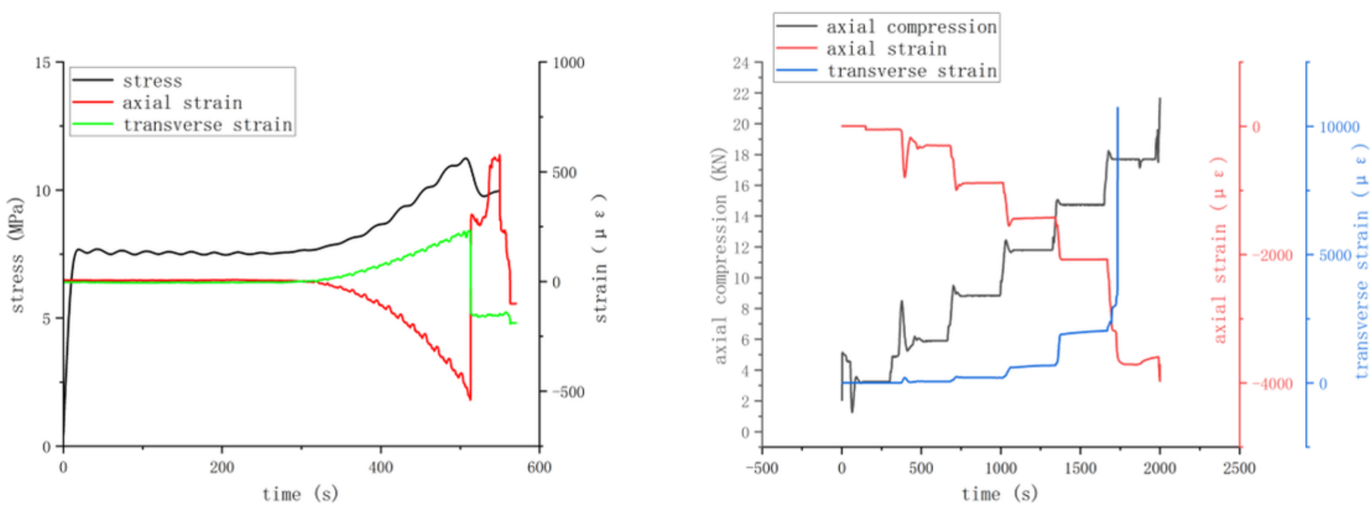

Figure 2

(a) Stress-strain diagram of specimen under uniaxial compression

(b) Stress-strain diagram of specimens under fractional loading

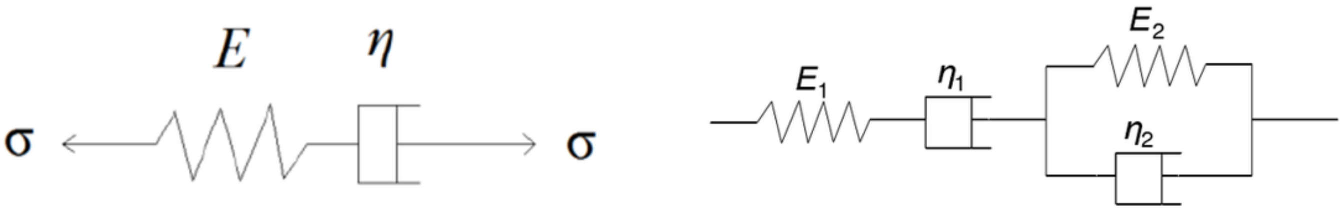

Figure 3

(a) Maxwell model

(b) Burgers mode

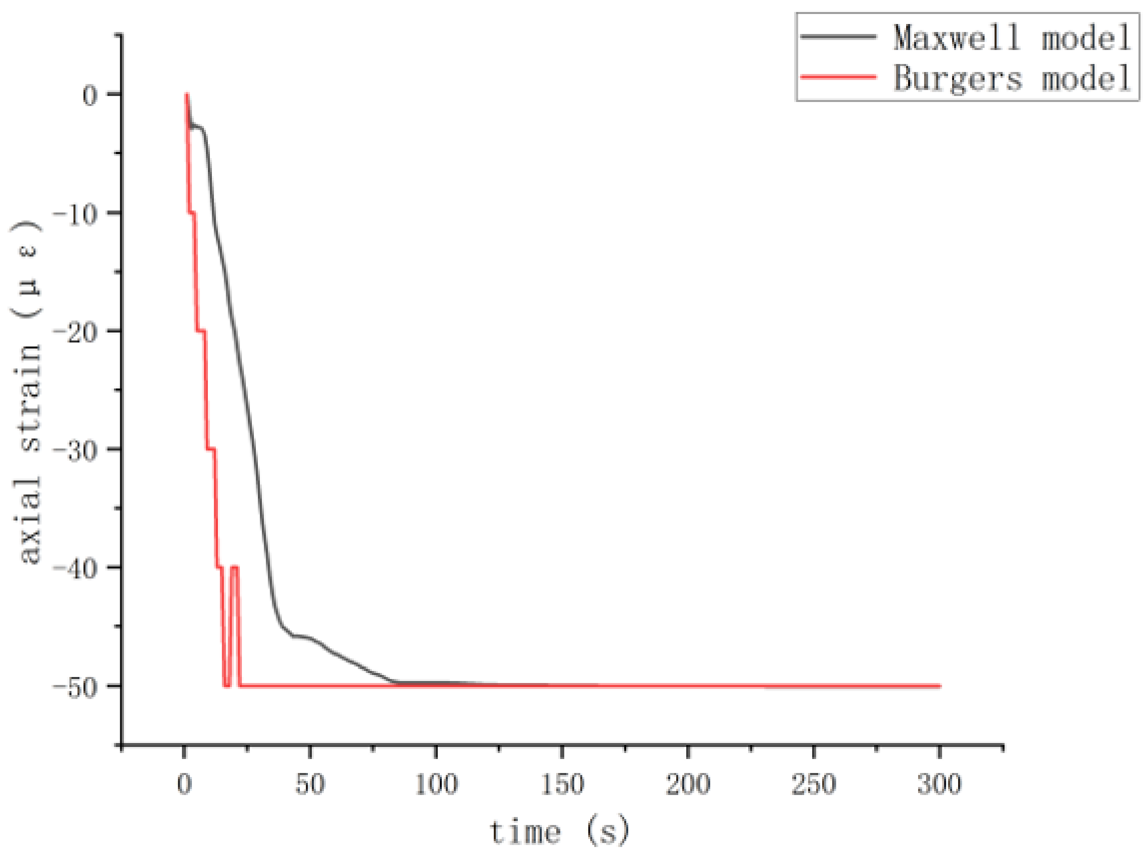

Figure 4

Numerical simulation diagram of different models

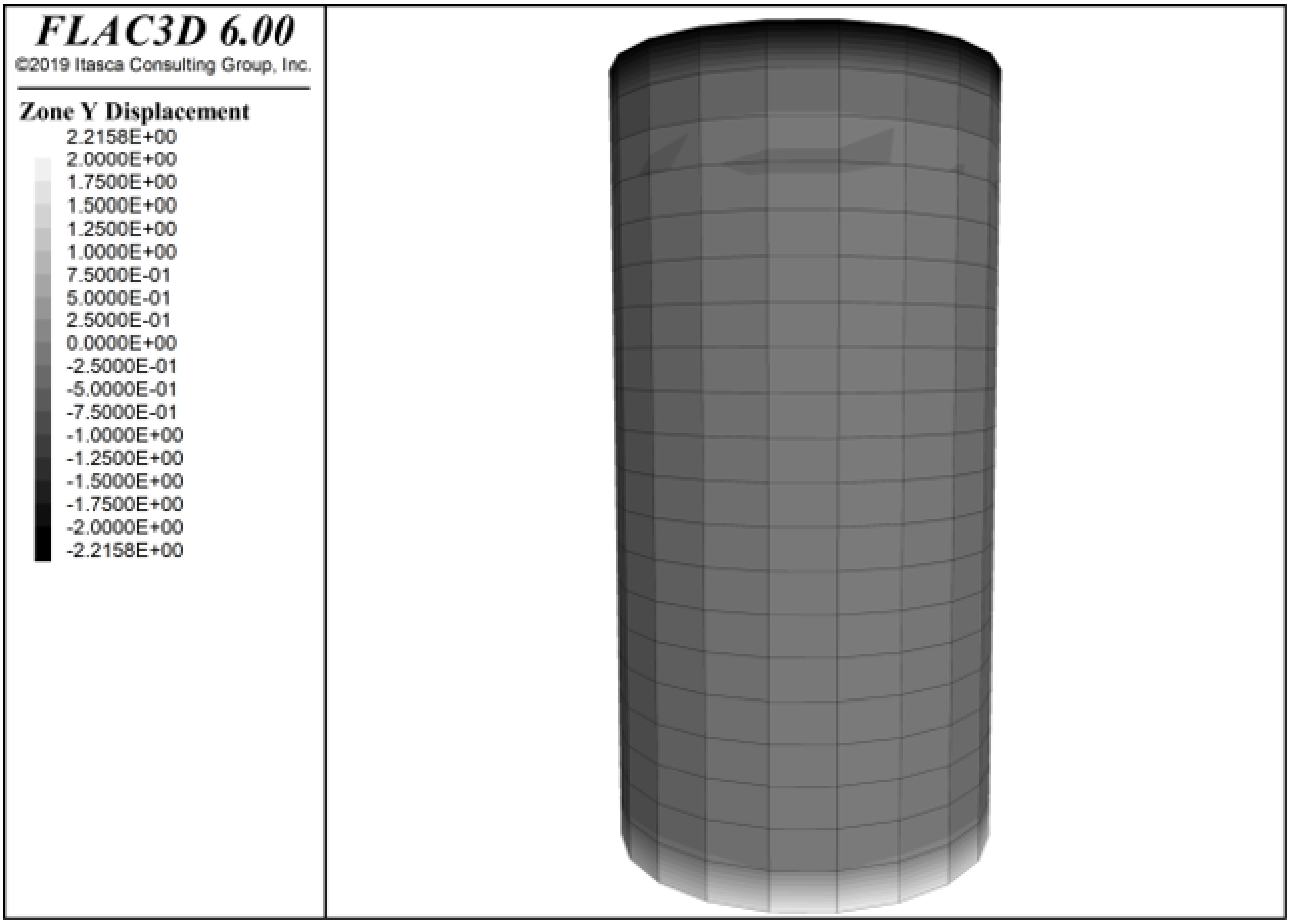

Figure 5

Numerical simulation diagram

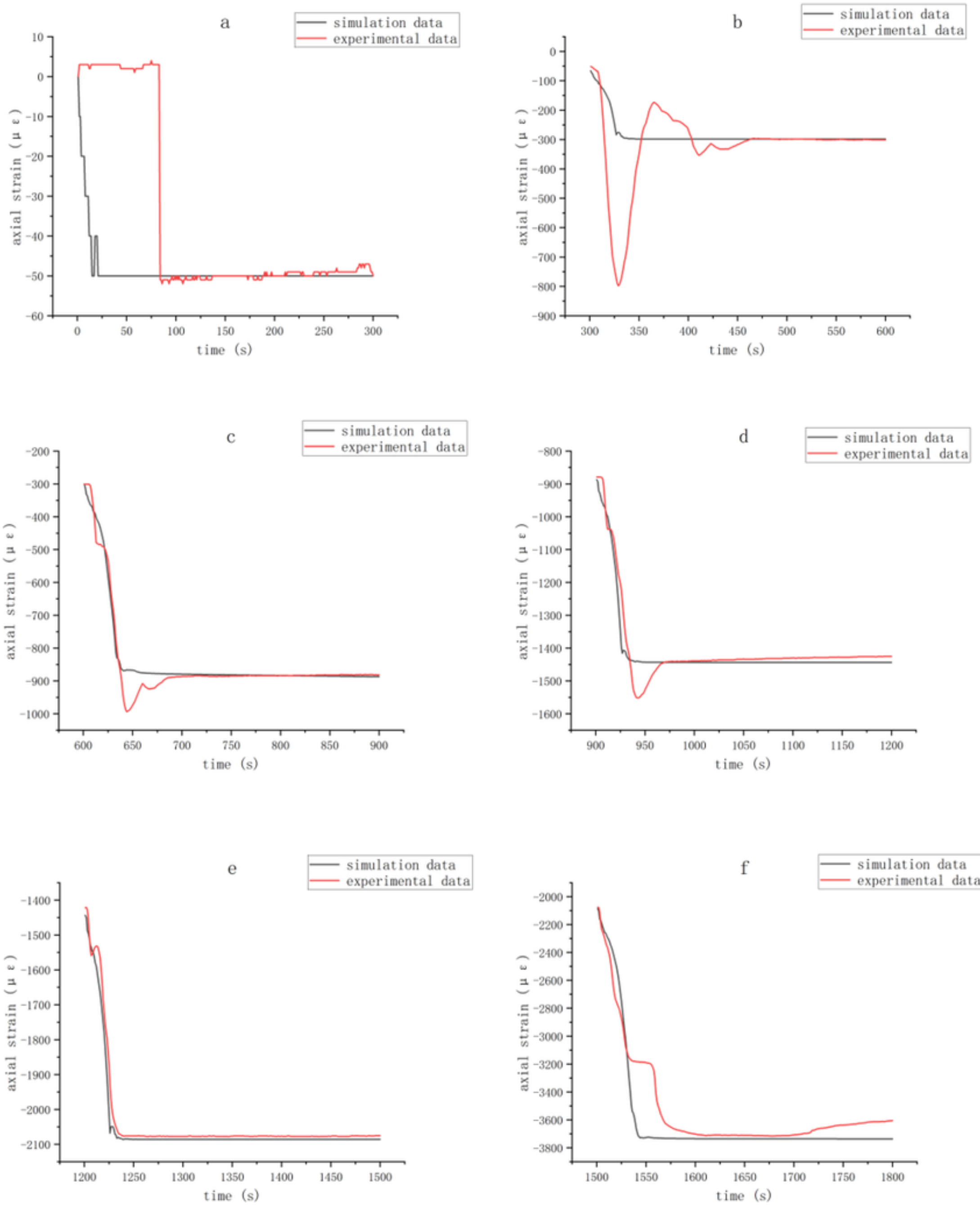

Figure 6

Results of different stress grading loading

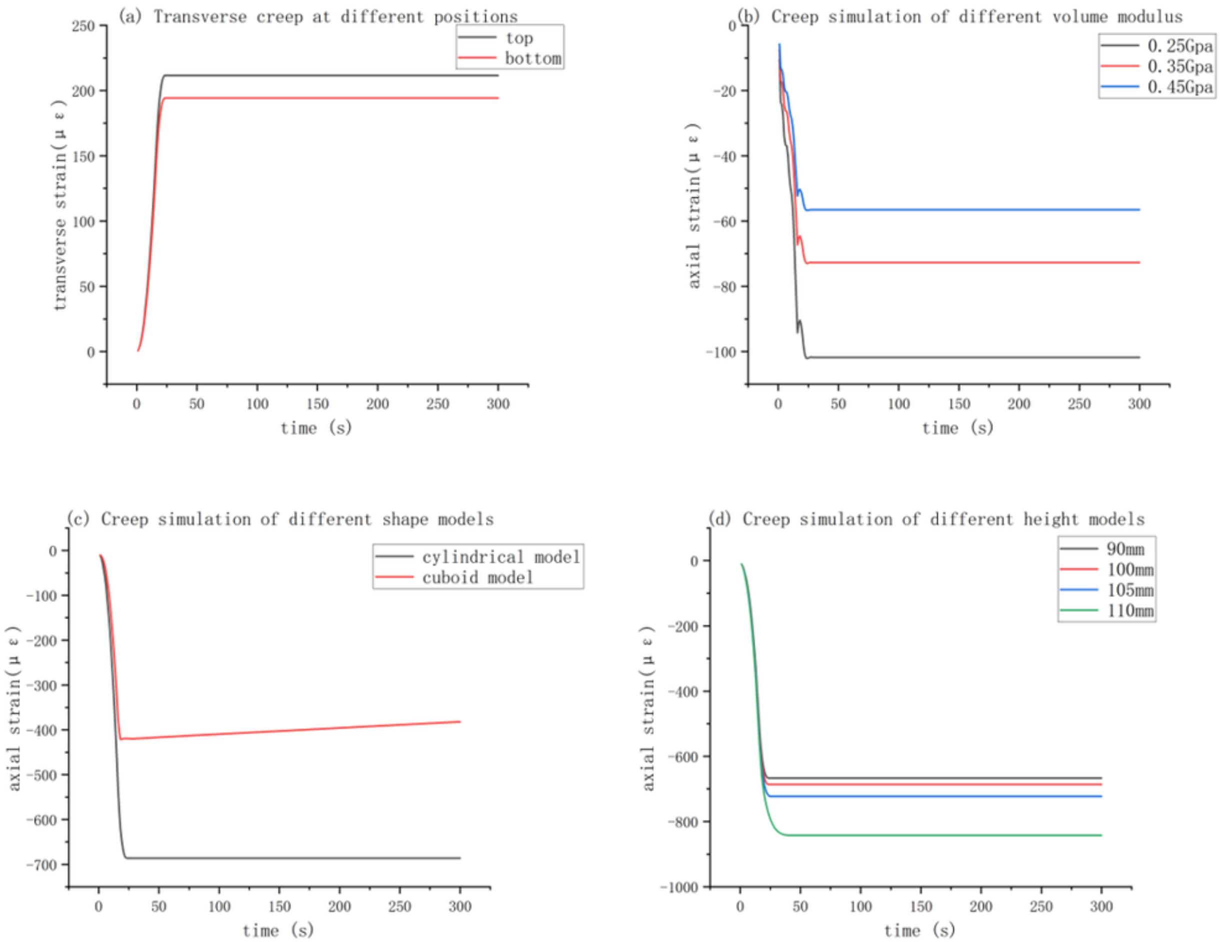

Figure 7

Creep contrast diagram