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Application of ultimate strain method in steel structure

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Abstract. Taking simply supported steel beam as an example, this paper attempted to apply the latest ultimate strain method of the numerical limit analysis to steel structures by using FLAC3D software. In the method, the numerical limit analysis was adopted to solve the ultimate strain of materials and regard it as the failure criterion for material points. Whether for tension or compression, steel is regarded as the ideal elastic-plastic material. The steel shall yield when reaching the ultimate limit of elastic strain under the yield load, and shall break under the ultimate limit of elastic-plastic strain. First of all, a direct pulling test was conducted on direct-pulling steel test pieces whose materials are the same with steel beams to obtain mechanical parameters of the steel material. Furthermore, the numerical limit analysis method was used to conclude the ultimate strain value of the steel material. Afterwards, a pure bending test was carried out on the simply supported steel beam until it's destroyed. FLAC3D was utilized to simulate the test process. In the end, numerical results were compared with the test results. Results showed satisfying consistence in the failure mode and ultimate bearing capacity of the steel beam. It proved that the ultimate strain method can be applied to steel structures and further studies on complicated structures can be conducted.

Key words. Ultimate strain method, Failure criterion, Simply supported steel beam, Pure bending test, Numerical limit method.

1. Introduction

Mature algorithms have been established for reinforced concrete structure in traditional architectural mechanics. However, at present, elastic-plastic mechanics is adopted in a great number of foreign and domestic software for calculation, such as extensive application of the numerical limit analysis based on elastic-plastic mechanics to geotechnical engineering. Theoretically speaking, such method can be equally used in the calculation of reinforced concrete structure, especially steel structures with desirable material homogeneity.

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When fragile materials such as concrete and casting iron are pulled, elastic-brittle tension failure happens and before failure the material is under an elastic status; when being compressed, elastic-plastic compression-shear failure happens and before failure the material is under a plastic status. Hence, corresponding tensile strength and shear (compression) strength are respectively used to judge failure. For soft steel, the steel is under elastic-plastic status no matter it's tension or compression, and elastic-plastic tension-shear or compression-shear occurs. At present, true tensile strength is not used in steel materials in project design. Instead, compression yield strength is employed. Shear strength can be obtained on this basis. The shear strength is 0.577 times yield strength when Mises yield criterion is followed; it's 0.5 times yield strength when Tresca yield criterion is observed.

The numerical limit analysis method has become the main method of solving safety coefficient of geotechnical engineering. It's not necessary to locate the failure surface first in this method. Stable safety coefficient and ultimate load can be obtained according to the overall failure conditions of the material. However, point failure, position of point failure and the whole process of failure evolution in the material cannot be known.

In recent years, the concept of ultimate strain has been spread in the world[1-6]. What determines material failure is ultimate strain rather than yield strength. Some software and measuring instrument of the world start regarding ultimate strain as the failure basis; the new-edition textbook *Concrete Structure* of China[7] explicitly pointed out while studying the hooped column with axial compression, "In case of failure, usually the longitudinal bar reaches the yield strength first. At this time, some loads can be added and in the end when the concrete reaches its ultimate strain value, the component breaks". It shows that ultimate strain is the true basis for failure but how to determine ultimate strain by calculation has not been solved yet.Recently, ABI Erdi and ZHENG Yingren, et. al. put forward the point failure criterion of ultimate strainultimate strain solution method and limit analysis method based on ultimate strain [8]. It can not only solve the stable safety coefficient and ultimate load of geotechnical engineering but also precisely present the whole process of failure evolution, including the crack initiation position, crack initiation safety coefficient, the position of the failure area, shape and scope in the material.

The limit analysis method based on ultimate strain(ultimate strain method for short) has been applied to geotechnical engineering, including slope engineering, ground engineering and tunnel engineering, with ideal effect being achieved [8-13]. This paper tried to apply it to the steel structure engineering. The shear strength of the steel material was calculated by conversion of tensile yield strength. It's calculated according to the elastic-plastic theory; strain was used to reflect the stress development process of the steel structure. Besides, ultimate strain failure conditions were adopted to judge whether it reached the failure status or not. As a result, the ultimate bearing capacity and failure mode of the structure were concluded. In the end, the steel beam test was verified to prove feasibility of the method.

2. The concept of ultimate strain

Fig. 1 demonstrates the stress-strain curve of ideal elastic and plastic material and hardening and softening material. At the elastic stage, the stress and strain show a linear relationship. The strain is elastic ultimate strain $\varepsilon y$when it just reaches yield; the ideal plastic is a horizontal straight line with constant stress and the strain keeps increasing, when the plastic strain develops to a certain extent, failure happens. At this time, the strain is elastic-plastic ultimate tensile(compressive) strain εf, simply known as ultimate tensile(compressive) strain. It can be noted from Fig. 1 that the material stress and strain present one-to-one correspondence at the elastic stage. When the material stress reaches the yield limit or reaches the elastic ultimate strain, the material yields and becomes plastic. Hence, stress or strain can be used to express yield conditions. However, after becoming plastic, due to constant stress, it cannot reflect the plastic distortion process of the material. Therefore, stress is just the necessary condition for failure rather than a sufficient condition. As a result, it cannot be regarded as the failure criterion of the material. It's obviously inappropriate to call stress yield condition as failure condition in plastic mechanics. Yet, at the plastic stage, strain keeps increasing with the stress until failure happens. It can demonstrate the plastic strain development process before failure. If the strain of a certain point in the material exceeds the ultimate strain, i.e. the peak strain in the hardening and softening curve, the point will come toa point failure. When it happens inrock soil and concrete materials, macroscopic fracture will occur; when it happens in steel, strain mutation will show up.Hence, it can be deemed as a condition for point failure of the material, thus making it up for lack of point failure criterion in current plastic mechanics [8–13]. The ultimate strain area connects in the material to form a overall failure surface, thus breaking the entire material. As a result, ultimate strain overall connection can be regarded as the criterion for overall failure in the material. Strength reduction method or overload method[14–18] in the numerical ultimate analysis methodology can be adopted for overall material failure either. It yields results that are consistent with calculation of the ultimate strain method.

For steel materials, if there's a yield terrace such as low-carbon steel, the yield limit is the minimum point of stress at the horizontal section. The yield point is the intersection point of the linear elasticity oblique line and yield limit horizontal line, being regarded as the yield limit of the ideal elastic-plastic material in mechanics. It's shown in Fig. 2a. If there's no yield terrace such as alloy steel, the yield limit is the point whose residual strain is 2? The intersection point of the horizontal line and the linear elasticity oblique line is treated as the yield limit of the ideal elastic-plastic material. It's shown in Fig. 2b. The strain before the yield limit point is elastic ultimate strain while the strain after is plastic strain. When the plastic strain reaches its limit, point failure happens in the material.

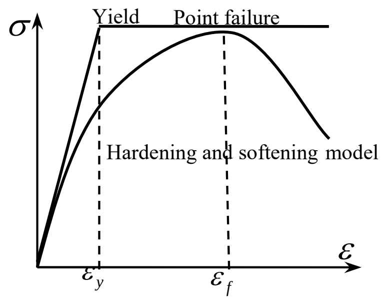


Fig. 1. The stress-strain curve of ideal elastic-plastic Materials and hardening and softening materials

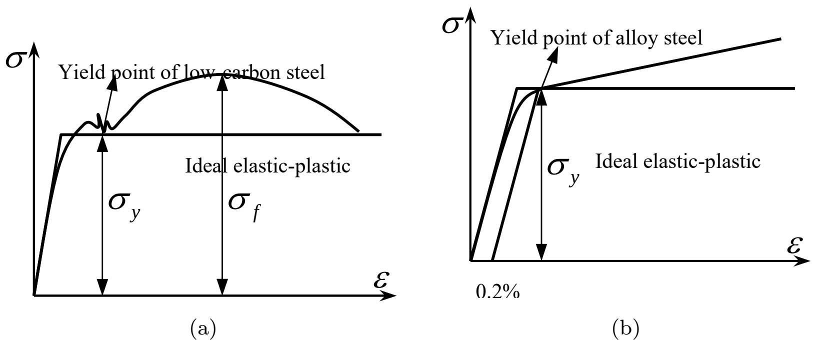


Fig. 2. Determination of ideal elastic-plastic Yield strain of steel materials

3. Solution method for ultimate strain of materials

3.1. Method overview

The elastic ultimate strain can be solved through formula [8] but it's difficult to some extent to come up with a formula for plastic ultimate strain. Even if a formula is provided, it's still complicated to work out a solution. Erdi, et. al. proposed in their paper the method of calculating the value of ultimate principal strain and shear strain. Detailed calculation methods can be viewed in the literature [8]. Its basic principle is to set up a suitable model, use the overload method for numerical limit analysis, keep loading at the top of the model and judge whether it reaches overall failure according to the overall failure criterion. In other words, when tiny load is added, the model's calculating displacement(or strain) suddenly changes or non-linear calculation turns to non-convergence from convergence. At this time, failure happens in only four units of the same kind. The failure units' average principal strain and shear strain under ultimate load are the ultimate principal strain and ultimate shear strain of the material.

3.2. Material yield stress and ultimate strain test

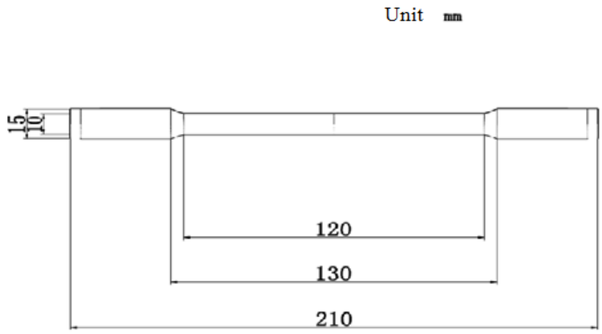


Fig. 3

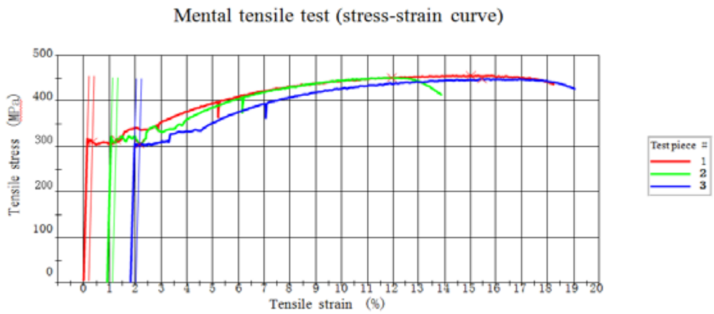


Fig. 4. Q235 steel tensile stress-strain curve(provided by the testing department)

Table 1. Test data of Q235 low-carbon steel

	Sample No.	Maximum value of tensile stress (MPa)	Elastic modulus (Chord 50 MPa – 200 MPa) (MPa)	Tensile stress at yield (Offset 0.2%) (MPa)	Tensile strain at yield (Offset 0.2%) (%)	Tensile stress when tensile strain is at peak value (%)
1	235-1	455.34	220089.96	309.83	0.34	14.99
2	235-2	450.54	218066.17	315.11	0.34	11.01
3	235-3	447.98	202698.75	305.46	0.35	13.60
Mean value		451.28	213618.29	310.14	0.34	13.20
Maximum value		455.34	220089.96	315.11	0.35	14.99
Minimum value		447.98	202698.75	305.46	0.34	11.01

The study is conducted based on the steel used in steel beam laboratory test of this paper. In order to obtain actual mechanical parameters required for numerical calculation, a material strength test was conducted first. Selected materials are Q235 low-carbon steel. A group of direct pulling tests was carried for the above material, and each group has three pieces. The test pieces are cylinders. Sizes are shown in Fig. 3. Test results are demonstrated in Fig. 4 and table 1.

Fig. 4 lists the test results of the Q235 low-carbon steel provided by the testing department. The stress-strain curves of test piece 2 and 3 in Fig. 4 were translated to the right in order not to overlap with test piece 1. Please refer to table 1 for data provided by the steel testing unit. According to the definition of dynamics, the tensile yield strain refers to the strain at the time of initial yield, i.e. elastic ultimate strain; the tensile ultimate strain is the product of the elastic ultimate strain and the plastic ultimate strain. The testing unit considers the plastic ultimate strain based on the offset of 0.2% so the tensile ultimate strain is 0.34%.

According to the Tresca criterion, the shear strength is σv=0.5, σy=155.07 Mpa, the tensile yield strain, that is, the elastic ultimate strain is 0.145%. Considering the offset of 0.2%, the tensile ultimate strain is 0.345%, as is shown in Table 2.

Table 2. Steel tensile test results of Q235 low-carbon steel

Sample Material	Tensile Stress (MPa)	Elastic Modulus (MPa)	Yield Stress (MPa)	Tensile Yield Strain (%)	Tensile Ultimate Strain (%) (Offset 0.2%)
Q235 Low-Carbon Steel	451	213618.29	310.14	0.145	0.345

3.3. Calculation of ultimate strain of steel

For the rectangular cross-section of simply supported steel beam, the steel beam is destroyed by tension and compression under pure bending. As a result, the ultimate tension strain or compression strain of the steel must be known. Given equivalence between the tension strength and compression strength of steel, this paper intended to establish a steel cube compression model to solve its ultimate compression strain.

Table 3. Physical-mechanical parameters of material in numerical calculation

Material	Elastic Modulus E/MPa	Poisson's Ratio v	Adhesion (Shear strength)c/ MPa	Internal Friction Angle $\varphi/°$
Q235	213618.29	0.3	155.07	0

FLAC3D software was adopted in this paper to set up a 15*15*15mm3 cube test piece. Mohr-Coulomb model was employed. When friction is not considered in metal, Tresca criterion is applied. It's a hexahedral mesh with 20×20×20 units with full restrain at the bottom. Measured value is used for the steel yield strength. In case of numerical calculation, table 3 shows the physical-mechanical parameters of the material.

12 key points are selected for the model with positions being shown in Fig. 5. Take the compression of the steel cube for example. The coordinates of key points are:

1(0.0075, 0.0075, 0.015), 2(0.0075, 0.0, 0.015), 3(0.0075, 0.0, 0.0075), 4(0.0075, 0.0, 0.00), 5(0.0075, 0.0075, 0.00), 6(0.0075, 0.0075, 0.0075), 7(0.0, 0.0075, 0.015), 8(0.0, 0.0, 0.015), 9(0.0, 0.0 , 0.0075), 10(0.0 , 0.0 , 0.00), 11(0.0 , 0.0075 , 0.00), 12(0.0 , 0.0075 , 0.0075).

The axial compression strain of all key points under each load is read to draw the strain-load curve chart as in Fig. 5.

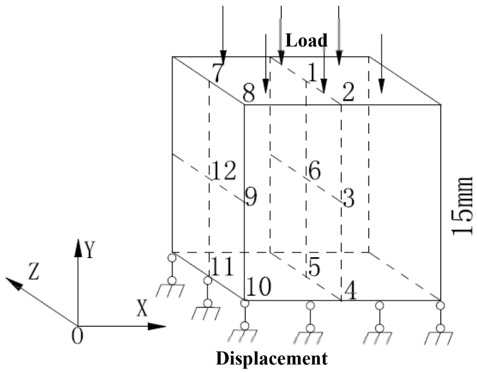


Fig. 5. Location of key points in the steel cube model

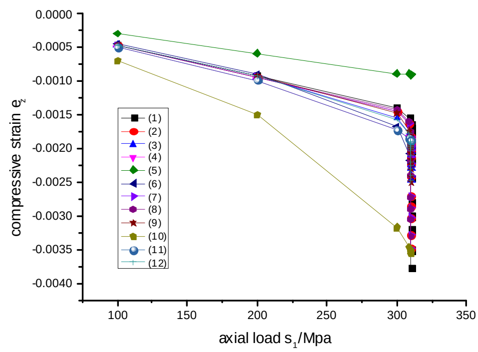


Fig. 6. Load-strain curve of q235 low-carbon steel key point

According to Fig. 6, the No. 10 point left bottom has the largest compression strain in the loading process and breaks first , other units show no failure, Hence, the average compression strain value of No. 10 point is regarded as the ultimate compression strain of Q235 low-carbon steel.. It can be noted from Fig. 7 and Fig. 8 that the key displacement converges and takes on a horizontal line when the load is 310.14Mpa, and when the load is 310.15Mpa, the key displacement doesn't converge and shows an oblique line. According to the overload method of the numerical limit approach, it can be judged that the ultimate load is 310.14Mpa, and after

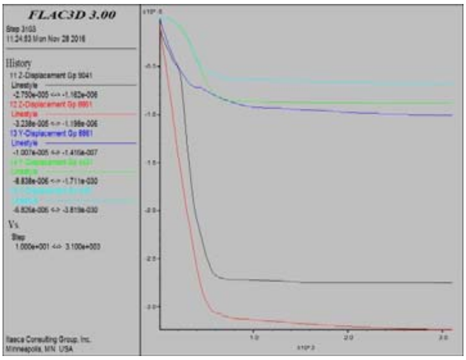


Fig. 7. Displacement curve of key point When the load is 310.14Mpa

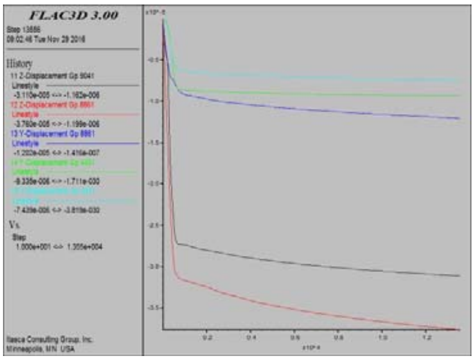


Fig. 8. Displacement curve of key point When the load is 310.15Mpa

calculation, the ultimate compression (tension) strain value (the total elastic-plastic strain value) is 3.52? The test results and numerical calculation suggest that the ultimate strain error of Q235 low-carbon steel is 2.03%. Table 4 and table 5 list the calculation results of ultimate strain of low-carbon steel and alloy steel with different specifications. As shown in the tables, the plastic ultimate strain of steel increases as the load is added. It's not a fixed value. The plastic ultimate principal strain of low-carbon carbon is 1.1‰∼1.9‰while that of alloy steel is 2.3‰∼3.2‰The actual strength of steel is usually greater than the nominal strength. Accordingly, the plastic ultimate strain will be increased to some extent.

Table 4. Ultimate strain of low-carbon steel

No.	Steel	E/GPa	v/1	φ/o	c/MPa	Ultimate Load /MPa	Elastic Ultimate Principal Strain ε1y	Elastic Ultimate Sheer Strain γy	Ultimate Principal Strain ε1f	Ultimate Sheer Strain γf
1	Q165	201	0.27	0	82.5	165.0	0.821×10-3	0.597×10-3	1.999×10-3	1.729×10-3
2	Q205	201	0.27	0	102.5	205.0	0.95×10-3	0.724×10-3	2.451×10-3	2.119×10-3
3	Q235	201	0.27	0	117.5	235.0	1.169×10-3	0.857×10-3	2.801×10-3	2.422×10-3
4	Q275	201	0.27	0	137.5	275.0	1.370×10-3	0.995×10-3	3.273×10-3	2.831×10-3

Table 5. Ultimate strain of alloy steel

No.	Steel	E/GPa	v/1	φ/o	c/MPa	Ultimate Load /MPa	Elastic Ultimate Principal Strain ε_{1y}	Elastic Ultimate Sheer Strain γ_y	Ultimate Principal Strain ε_{1f}	Ultimate Sheer Strainγ_f
1	Q335	206	0.3	0	167.5	335.0	1.626×10-3	1.221×10-3	3.959×10-3	3.559×10-3
2	Q345	206	0.3	0	172.5	345.0	1.675×10-3	1.257×10-3	4.077×10-3	3.665×10-3
3	Q370	206	0.3	0	185	370.0	1.796×10-3	1.348×10-3	4.367×10-3	3.926×10-3
4	Q390	206	0.3	0	195	390.0	1.893×10-3	1.421×10-3	4.596×10-3	4.131×10-3
5	Q400	206	0.3	0	200	400.0	1.942×10-3	1.457×10-3	4.718×10-3	4.240×10-3
6	Q420	206	0.3	0	210	420.0	2.039×10-3	1.530×10-3	4.957×10-3	4.457×10-3
7	Q440	206	0.3	0	220	440.0	2.136×10-3	1.603×10-3	5.185×10-3	4.662×10-3
8	Q460	206	0.3	0	230	460.0	2.233×10-3	1.676×10-3	5.413×10-3	4.866×10-3

4. Test design

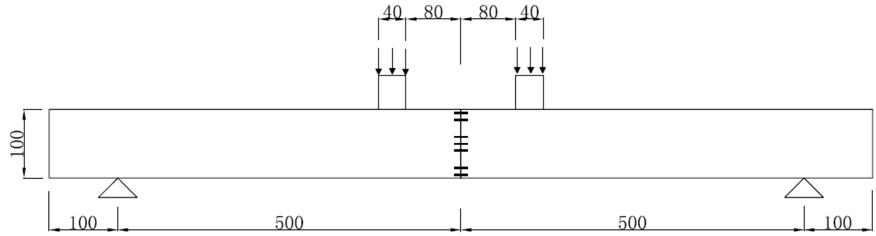
In order to verify the feasibility of ultimate strain application in steel structure, a rectangular cross-section of simply supported steel beam was designed to respectively conduct a laboratory test and numerical calculation, to verify whether the position of ultimate strain point is consistent with its ultimate load or not can provide new failure standards for steel beam calculation.

4.1. Size and material of test piece

The test piece is a rectangular cross-section and its size is $l \times h \times b = 1200$ mm$\times$ 100mm $\times$ 50mm; the size of the cushion block is 40×50×50mm3. Even load is added. Detailed sizes can be viewed in Fig. 9.

4.2. Steel beam strain monitoring design

As demonstrated in Fig. 9 (b), two steel strain gauges are pasted at the top and bottom of the beam cross-section. Seven strain gauges are pasted on the side with the neutral surface as symmetric surfaces. The numbers at the top is 1 and 2; 10 and 11 at the bottom and 3, 4, 5, 6, 7, 8 and 9 on central sides, the distance between



(a) Size of the simply supported beam and loading model

(b) Arrangement of gauges for the steel beam cross-section

Fig. 9. Model of simply supported beam (unit: mm)

Point 9 and the bottom is h/20 while the distance between Point 8 and the bottom is h/6.7. h represents the beam height.

4.3. Loading design

It can be seen from Fig. 9 (a) that supports are set at the point of 100mm from both ends of the beam. Two cushion blocks with a size of 40×50×50mm3 are placed in the middle. Even load is imposed on cushion blocks. Step loading is adopted until a gauge starts overflowing.

5. Simply supported beam test

5.1. Loading system

Step loading (kN) is adopted: $0 \to 50 \to 100 \to 110 \to 115 \to 117 \to 119 \to 122 \to 123 \to 126 \to 133 \to 136 \to 141 \to 148 \to 151 \to 156 \to 159 \to 164 \to 167$.

5.2. Analysis of steel beam strain monitoring results

Fig. 10 shows the strain-load curves of strain monitoring points in Q235 low-carbon steel beam. Table 6 shows the corresponding strain value of Point 8, 9, 10 and 11 which are closely related with calculation results under different level of test loads. It can be noted that the strain value of monitoring points in the compression area and the tension area is basically distributed in a symmetric way, which is consistent with the stress features of pure bending. When the load is 110KN, the principal strain of Point 10 and 11 is greater than the elastic ultimate strain 0.145%, which indicates that the points have entered the plastic deformation stage through the linear elastic stage; when the load is added to 133KN, Point 8 and 9 reach the elastic ultimate strain; Point 11 reaches the ultimate strain of 0.352% under the load of 151KN; Point 9, 10 and 11 reaches ultimate strain when the load is 156KN; therefore, the bottom ultimate strain of the steel beam is between 151 and 156KN. The estimated value is 153KN. As greater loads are imposed, all points undergo dramatic changes and the deformation is compounded, thus making it unsuitable for bearing, which means the steel beam has broken as a whole.

Pursuant to China's *Code for Steel Structure Design* (GB50017-2003) [19], the plastic deformation depth of the cross-section should be no more than 1/8 of the cross-section height. In other words, when the stress of the 1/8 point of the cross-section's height reaches the yield stress, it's defined as failure.Based on this standard, the position of Point 8 has surpassed the 1/8 of the cross-section's height. When the load is 133KN, the Q235 steel beam has become plastic and its stress reaches yield stress, which meets requirements of existing norm for steel beam failure. Hence, pursuant to regulation of *Code for Steel Structure Design*, the steel beam has been under a failure status, and the ultimate load of its failure is 133KN on the whole.

Table 6. Strain value of no. 8, 9, 10 and 11 points in Q235 low-carbon steel under varied levels of test loads

Load/KN	0	50	100	110	115	117	119	122	123
monitoring point 8	0	0.37‰	0.91‰	1.07‰	1.15‰	1.18‰	1.21‰	1.25‰	1.27‰
monitoring point 9	0	0.47‰	1.18‰	1.38‰	1.48‰	1.52‰	1.56‰	1.61‰	1.64‰
monitoring point 10	0	0.56‰	1.34‰	1.55‰	1.66‰	1.70‰	1.74‰	1.79‰	1.82‰
monitoring point 11	0	0.57‰	1.41‰	1.64‰	1.75‰	1.79‰	1.83‰	1.88‰	1.92‰
Load /KN	126	133	136	141	145	148	151	156	159
monitoring point 8	1.32‰	1.45‰	1.53‰	1.66‰	1.79‰	1.93‰	2.13‰	2.84‰	7.13‰
monitoring point 9	1.70‰	1.88‰	2.01‰	2.22‰	2.43‰	2.65‰	2.94‰	3.89‰	9.89‰
monitoring point 10	1.89‰	2.09‰	2.23‰	2.48‰	2.71‰	2.96‰	3.38‰	4.67‰	11.43‰
monitoring point 11	1.99‰	2.20‰	2.37‰	2.66‰	2.93‰	3.22‰	3.58‰	4.70‰	11.91‰

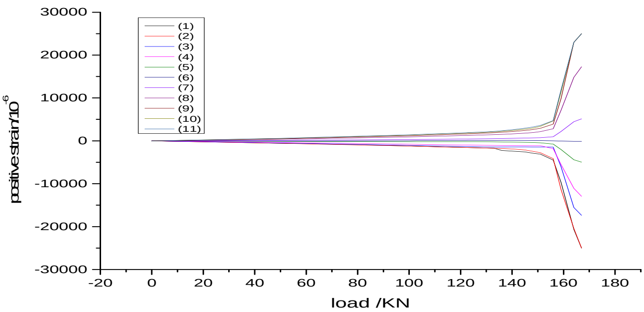


Fig. 10. Strain-load curve of steel monitoring points

5.3. Failure conditions of the steelbeam

Fig. 11. Development of transformation

Three parallel lines were marked on the front side of the steel beam so as to observe deformation features of the steel beam. After reaching the failure load, the steel beam deformation was compounded. Until the last level of 167 KN was imposed, some strain gauges overflew. At that time, loading was stopped. The final deformation status is reflected in Fig. 11.

6. Numerical simulation

6.1. Numerical calculation model

This paper adopted FLAC3D software and Mohr-Coulomb model for calculation. The steel beam grid is 240×5×10 and the cushion block grid is 8×5×5. Even load was imposed on the top of cushion blocks. It should be pointed out that the geometric size of cushion blocks will have impact on the result of numerical calculation. Therefore, the size of cushion blocks in the numerical simulation must keep consistent with those in the test. Fig. 12 shows the steel beam grid and positions of monitoring points which are the same with those in the test.

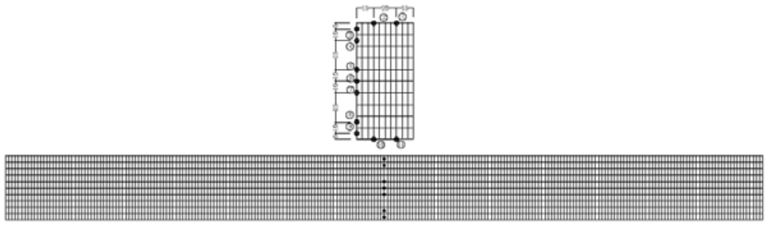


Fig. 12. Steel beam grid and positions of monitoring points

6.2. Analysis of Calculation Results

Fig. 13 presents the load-strain curve of Q235 low-carbon steel monitoring points based on numerical calculation. Table 7 lists the corresponding axial strain value of Point 8, 9, 10 and 11 which are closely related with calculation under key loads. Table 8 demonstrates the ratio between the deflection and span of steel beam under key loads.

Table 7. Calculated strain value of point 8, 9, 10 and 11 under key loads

Load/KN / Point	100	121	135	156.4	162.5
Point 8	0.83‰	1.13‰	1.46‰	2.74‰	3.53‰
Point 9	1.02‰	1.38‰	1.78‰	3.35‰	4.24‰
Point 10	1.08‰	1.46‰	1.89‰	3.53‰	4.48‰
Point 11	1.08‰	1.46‰	1.89‰	3.53‰	4.48‰

Table 8. Deflection of steel beam under key loads

Load /KN	50	100	121	135	156.4	162.5
Deflection/mm	1.15	2.3	2.92	3.50	4.94	5.61
Deflection/Span	1/870	1/435	1/342	1/286	1/202	1/178

It can be known from Table 8 and Table 9 that when the load is 100KN, all points are under an elastic status; when the load is 121KN, Point 10 and 11 at the bottom reach elastic ultimate strain and enter plastic status; when the load is 135KN, Point 8 reaches the elastic ultimate strain and enters the plastic status, which reflects that the ultimate strain under the current approach is 135KN; in case of 156.4KN, Point 10 and 11 at the bottom come to the ultimate strain and enter the failure status. At this time, the deflection-span ratio is 1/202. In case of 162.5KN, Point 8, 9, 10 and 11 reach ultimate strain and enter the failure status. It can be deemed that the steel beam breaks on the whole. The deflection-span ratio is 1/178, but this time the numerical calculation has entered the destruction phase, the calculated data and the

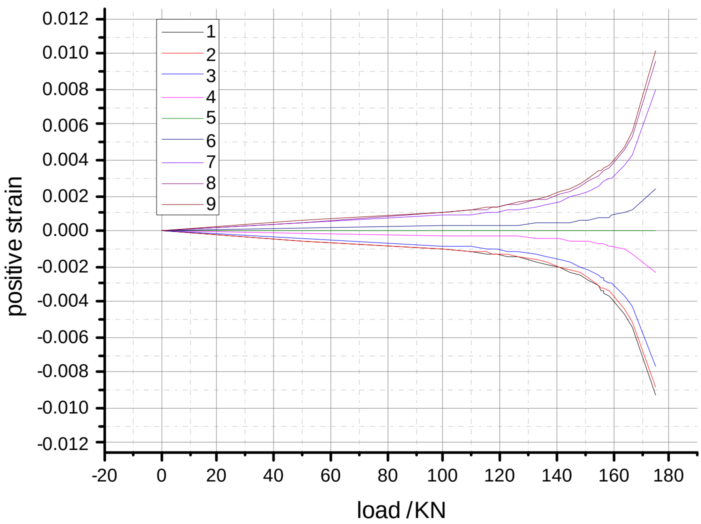


Fig. 13. Calculated strain-load curve of steel monitoring points

measured data does not match, should not be used. According to the regulation on the permissible deflection value of bent components in Appendix A of China's Code for Steel Structure Design (GB50017-2003) [19], it's suggested that the ultimate load defined in this paper shall be adopted as the failure standard for components whose permissible deflection-span ratio is more than 1/200. The value can be set 156.4 KN. The calculation standards of the ultimate strain method are observed. The ultimate load of the method in this paper is 1.158 times greater than that of the existing method. The standard deflection norm can be followed for components whose permissible deflection-span ratio is less than 1/200.An inverse computation is conducted through deflection to work out the ultimate load.

Fig. 14 demonstrates the load-strain chart of Point 11 on the beam respectively under numerical calculation and the test. Apparently, the two curves before failure are extremely approximate, and both of them enter the failure status after reaching the ultimate strain of 3.52? Then the strain start dramatic growth, which manifests that the calculation results coincide with the test results and meanwhile it's feasible to regard the ultimate strain of steel as the failure basis.

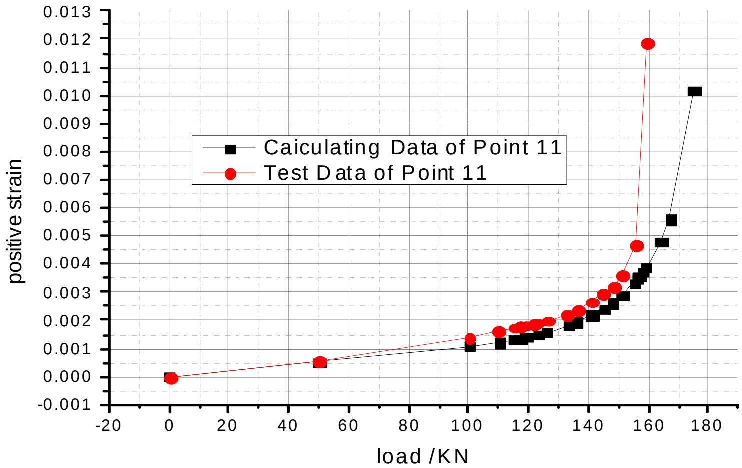


Fig. 14. The Load-strain chart of point 11under numerical calculation and the test

6.3. Result comparison of the steel beam test and the ultimate strain method

According to the results of the steel beam test and the calculation of ultimate strain method, the existing failure standards in steel beam calculation are changed. It's defined that when any point of the steel beam reaches the ultimate strain, it enters the failure stage because the strain undergoes rapid growth after the steel beam comes to its ultimate strain and its majority immediately passes into failure. As defined above, given the calculation result, the ultimate load of Q235 steel beam is between 156.4 and 162.5KN; in terms of the test results, the ultimate load is between 151 and 156KN. The two results are close. Hence, it indicates that the ultimate strain method is suitable for steel as well. Table 9 lists the result comparison of the steel beam test and the calculation of ultimate strain method.

Table 9. Result comparison of the steel beam test and the ultimate strain method

Item	Test Value	Value of Numerical Calculation	Error/%
Load when Point 10 and 11 reach elastic ultimate strain/kN	110	121	10
Load when Point 8 reach elastic ultimate strain/kN	133	136	2.3
Load when Point 10 and 11 reach elastic - plastic ultimate strain/kN	151∼156 (estimated value 153)	156.4	2.2
Load when Point 8 reach elastic - plastic ultimate strain/kN	156∼159 (estimated value 157)	162.5	3.5

7. Conclusions

(1) Based on the theory of plasticity, the elastic-plastic material firstly enters into the plastic yielding phrase, and then it continues to develop until the strain reaches to the limit value, which is the real sign of material damage.

(2) In accordance with results of the steel beam test and the calculation of ultimate strain method, based on the failure criterion of ultimate strain, it's defined that when the strain of any point or the point at the h/8 from the bottom of the steel beam reaches the ultimate strain, it's deemed as failure. It's because all points show rapid increase in their strains after reaching the ultimate strain point, and the steel beam deforms on the whole and exceeds the applicable scope of projects. The ultimate strain in the method of this paper is 156.4, which is 1.158 times greater than the ultimate load in the existing method.

(3) The ultimate strain value of the low-carbon steel and alloy steel is proposed on the basis of calculation, and is applied to the steel beam test and numerical calculation. The ultimate load of the steel beam obtained in the ultimate strain method is basically consistent with that acquired from the test, which means that the application of the ultimate strain method to steel structure calculation is feasible.

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