# The Application of GTN damage model in mechanical performance of building steels

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***ABSTRACT:*** *Damaged steel connection is usually the leading cause inducing steel structure related accidents. It is more scientific and reasonable to analyze damage of steel and steel connections in micromechanical perspective. Gurson-Tvergaard-Needleman (GTN) mode is the most widely applied micromechanical damage model currently; however, it has not been promoted in construction field. Therefore, this study attempts introducing GTN micromechanical damage model into study of mechanical performance of building steels. Test specimen taken from Q354 low alloy steels and austenitic 304 hot rolling stainless steel tubes are processed into smooth and notch specimen and then unidirectional tensile test is performed to identify material and damage parameter of two different steel materials. Comparing results with numerical stimulation results, we find GTN damage model is able to accurately predict breaking point of Q345 low alloy steel specimen, but the GTN damage model constructed based on stress-strain relationship stimulated by Ramberg-Osgood curve cannot predict mechanical behaviors of austenitic 304 stainless steels.*

**Keywords:** GTN, Building steel, Uniaxial tension, Damage parameters

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## 1. Introduction

Material damage varies on forms. For example, ductile material such as metal emerging in the form of microvoid grows, expands and aggregations under external force until certain scale macrocracks emerge, leading to final damage. Thus before constructing a reasonable and refined material constitutive model, we should not only consider damage of steels as well as damage mechanism, but also needs to explore ductile fracture of steel by analyzing nucleation, growth and aggravation effect of internal holes and combining micromechanical damage process and macro-stress state together.

As to damage mechanics, scholars from China generally focus on micro-damage mechanics. Based on plastic strain, Shen Zuyan [1] put forward a proper steel component damage model and confirmed its parameter through low cycle fatigue test. Song

Zhensen [2] obtained a component damage model under triaxial stress by applying one-dimension damage theory into three-dimension stress and representing damage model with equivalent plastic strain. Considering the influence of triaxial stress on structure performance in earthquake, Xu Longhe [3] proposed a damage model based on equivalent plastic strain and specific energy double control. Besides, Fan Feng et al. [4] fitted coefficients in material constitutive equation involving damage based on the coincidence degree of trial curve and numerical curve. Wu Zhenyu [5] established a mixed hardening elastoplastic constitutive model using bilinear mixed hardening model and Lemaitre damage model. Dong Jie et al. [6] developed microvoid damage evolution equation involving materials considering damage and thermal softening.

GTN theory applied in finite element analysis is now one of the most widely used metal constitutive damage models in China and foreign countries. Zhang [7] once made a systematic study on GTN model, and proposed a new failure criterion of G-T model and attempted to use it into analysis in cycle load case. Moreover, Besson and Guillemer-Neel [8] once tried adding kinematic hardening effect into GTN model. Researches involving GTN is limited in China. Wang Guozhen et al. [9] once made finite element stimulation prediction on ductile fracture of notched round steel bars with different notch root radius using GTN damage model equipped by ABAQUS. Jiang Fei [10] explored the damage on materials used to make pressure vessel using ductile damage theory and GTN model. Based on such research background, this study applied GTN damage model to study mechanical performance of building steels based on damage parameters extracted by steel material characteristic test.

## 2. Basic Theory of GTN Model And Determination of Parameters

o Tdate, the most widely applied ductile fracture model was put forward by Gurso in 1975. That model describes the relationship between void extension and plastic deformation quantity. After that, some other scholars [11,12] made a series of studies on that model to improve it. Application and development of computer technology helps GTN model to be more applied in study of ductile fracture, for example, in pipe crack prediction [13] and metal press forming [14]. Based on the summary on previous experience, Gurson proposed using cell model with microvoids inside which locates in large finite model to describe the impact of microvoid damage on plastic deformation of materials. First, he focused on materials with cylindrical cavity, and put forward yield function of porous material based on that. That yield function contains parameters like equivalent stress, hydrostatic pressure strain and the volume of voids. Next, he made a research on spherical cavity and put forward the following yield function of spherical cavity.

$$\Phi = \left(\frac{\sigma_{eq}}{\sigma_m}\right)^2 + 2f\cosh\left(\frac{3}{2}\frac{\sigma_h}{\sigma_m}\right) - (1+f^2) = 0 \qquad (1)$$

In the formula, $\sigma_{eq} = \sqrt{\frac{3}{2}S_{ij}S_{ij}}$ is macro Von Mises equivalent stress;

$\sigma_h = -\frac{1}{3}\sigma_{kk}$ is macro hydraulic stress;

$S_{ij} = \sigma_{ij} - \frac{1}{3}\sigma_{kk}\delta_{ij}$ is deviatoric stress component of macro stress;

$\sigma ij$ is flowing stress component;
$\delta ij$ is kronecker mark.

$\sigma m$ is equivalent stress of basis material; subscript m stands for basis material; $f$ is volume fraction of holds. When $f = 0$, the above formula would degrade to Von Mises yield function.

Classical plasticity theory assumes plastic volume is incompressible and yield of materials is in no correlation to hydraulic stress. However, yield surface of Guison model considers the impact of macro hydraulic stress and connects yield of materials with damage to reflect constant degradation of materials in deformation process.

Damage parameters of GTN model can be divided into four parts [15]. The first part is basic material properties of plastic or destruction region of materials, i.e., stress strain relationship of materials with no void. This study adopted standard J0 plastic flow theory and represent uniaxial mechanical behavior of materials with real stress strain curve obtained from uniaxial tensile test. The second part is q1, q2 and q3 relating to strengthening of base materials (q3= q1*q2). Tvergaard [16] concluded from

study on medium strengthening materials (1/n=0.1) that, when q1=1.5 and q2=1.0, results of Gurson model was nearly the same as results of micro unit model. Faleskog et al. [17] found that, values of q1 and q2 was in a correlation with strengthening index n and ratio of yield stress to elasticity modulus σ0/E. They drew the relationship between q1, q2, n and σ0/E into a relationship figure shown in table 1.

| **Hardening index 1/n** | **$\sigma_0$/E=0.001** | **$\sigma_0$/E=0.002** | | | | **$\sigma_0$/E=0.004** |
|---|---|---|---|---|---|---|
| | **q1** | **q2** | **q1** | **q2** | **q1** | **q2** |
| 0.25 | 1.89 | 0.953 | 1.82 | 0.976 | 1.75 | 1.011 |
| 0.050 | 1.62 | 0.949 | 1.58 | 0.975 | 1.47 | 1.012 |
| 0.075 | 1.53 | 0.938 | 1.44 | 0.961 | 1.32 | 1.003 |
| 0.10 | 1.56 | 0.901 | 1.45 | 0.932 | 1.28 | 0.981 |
| 0.15 | 1.77 | 0.831 | 1.67 | 0.855 | 1.50 | 0.900 |
| 0.20 | 1.95 | 0.780 | 1.88 | 0.801 | 1.72 | 0.835 |

Table 1. value of q1 and q2

The third part is average equivalent plastic strain of void nucleation εn, standard deviation of nucleation strain Sn, void volume fraction of nucleation particle *f* n, critical volume fraction when voids begin to gather and void damage volume fraction *f* F.

### 3. Experimental Object And Method

The most effective way to study damage fracture of ductile metal is performing notched round bar tensile test. This study aims to observe damage features of ductile metal by carrying out unidirectional tensile test on standard specimen, obtain basic mechanical parameters of material by standard specimen tensile test as well as damage parameters of GTN model by comparing load-displacement curve obtained by notched round bar specimen tensile test with stimulation results.

Materials used in the study are Q345 low alloy steels and austenitic 304 hot rolling stainless steel tubes which are often used in building. Test specimen is made by the materials cut from circular steel tubes (Φ216×20mm) made up of the above two materials (figure 1). Diameter of coverage area of smooth specimen is 10 mm. To obtain different-level stress triaxiality, notched specimen uses R1, R2 and R4 specimen whose radius is 1 mm, 2 mm and 4 mm respectively and minimum cross section diameter is 5 mm.

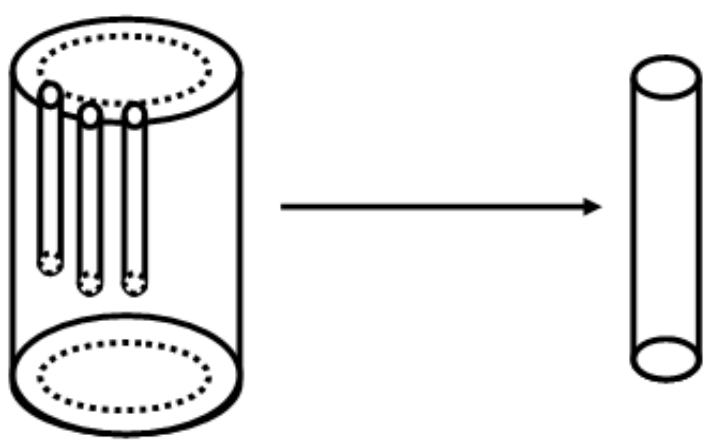


Figure 1. Material collection of specimen

This test adopts chuck displacement to control loading. According to criteria of American Society for Testing Material (ASTM), loading rate of smooth round bar specimen and notched specimen is kept at 0.3mm/min and 0.12mm/min. Longitudinal deformation of the specimen is measured by extensometer with 12.5 mm gauge length.

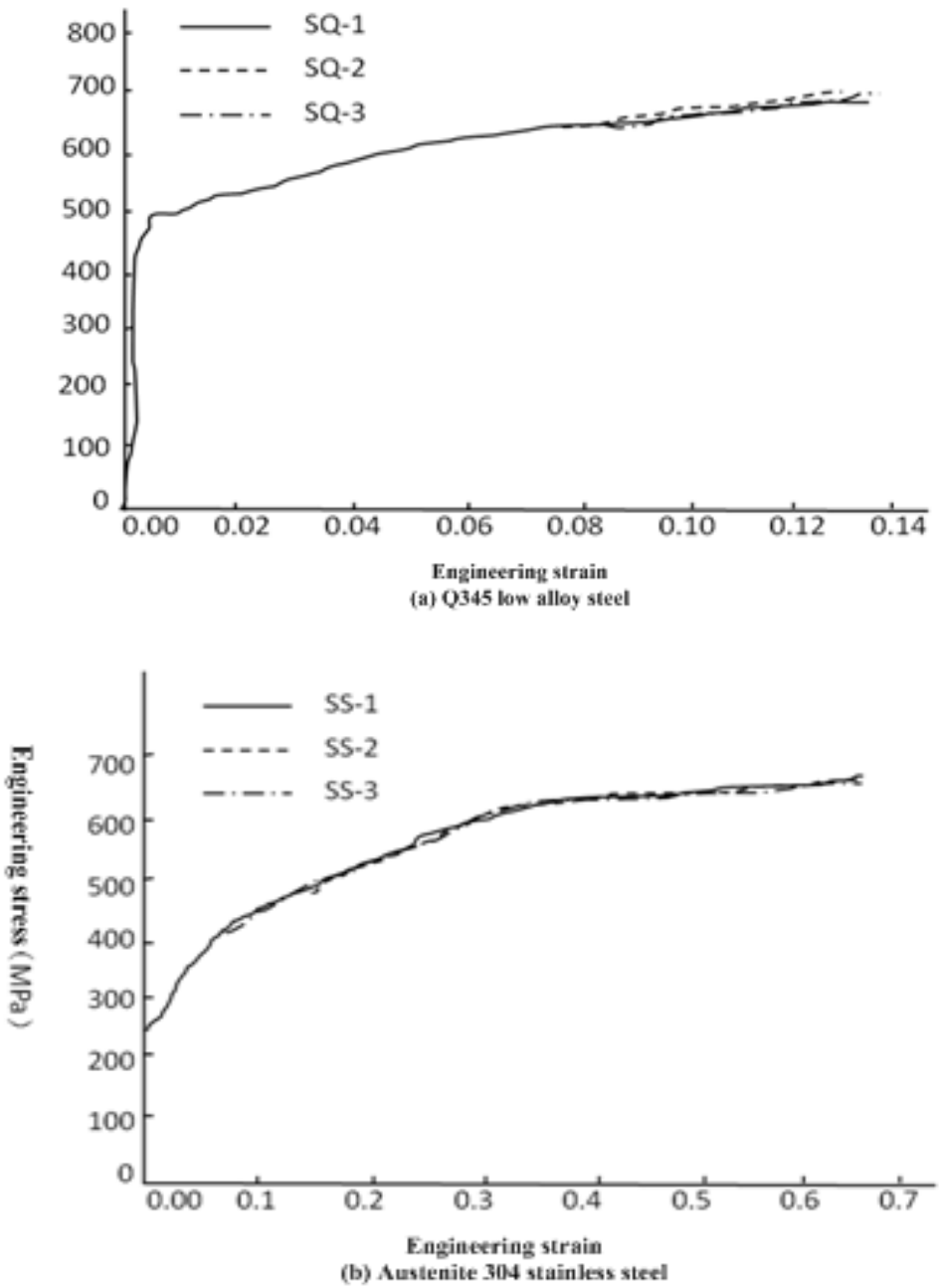



Figure 2. nominal stress-strain curve of steel

**3.1 Test phenomenon**

As to smooth specimen, when longitudinal deformation reaches a certain value, the middle part of the specimen would neck down until fracture.

As to notched specimen, deformation usually occurs at notch.

## 4. Test Results

### 4.1 Smooth round bar test results

Data obtained in uniaxial tensile test is expressed as nominal strain εnom and nominal stress σnom. Calculation formula for εnom and σnom is

$$\varepsilon_{nom} = \Delta l / l_0 \quad (2)$$

$$\sigma_{nom} = F / A_0 \quad (3)$$

In the formula, Δ1 refers to variation of gauge length of extensometer, l0 refers to gauge length of extensometer, F is loading and A0 is initial cross sectional area of gauge segment of specimen.

Figure 2 is the nominal stress-strain curve of different test specimen made up of two kinds of steels. Results of QS-3 are taken for research, as the figure shows that, results of QS-1 and QS-3 specimens nearly coincide and results of QS-2 specimen slightly disperse; moreover, results of SS-2 are taken for research as results of SS-1, SS-2 and SS-3 almost coincide, with little discreteness.

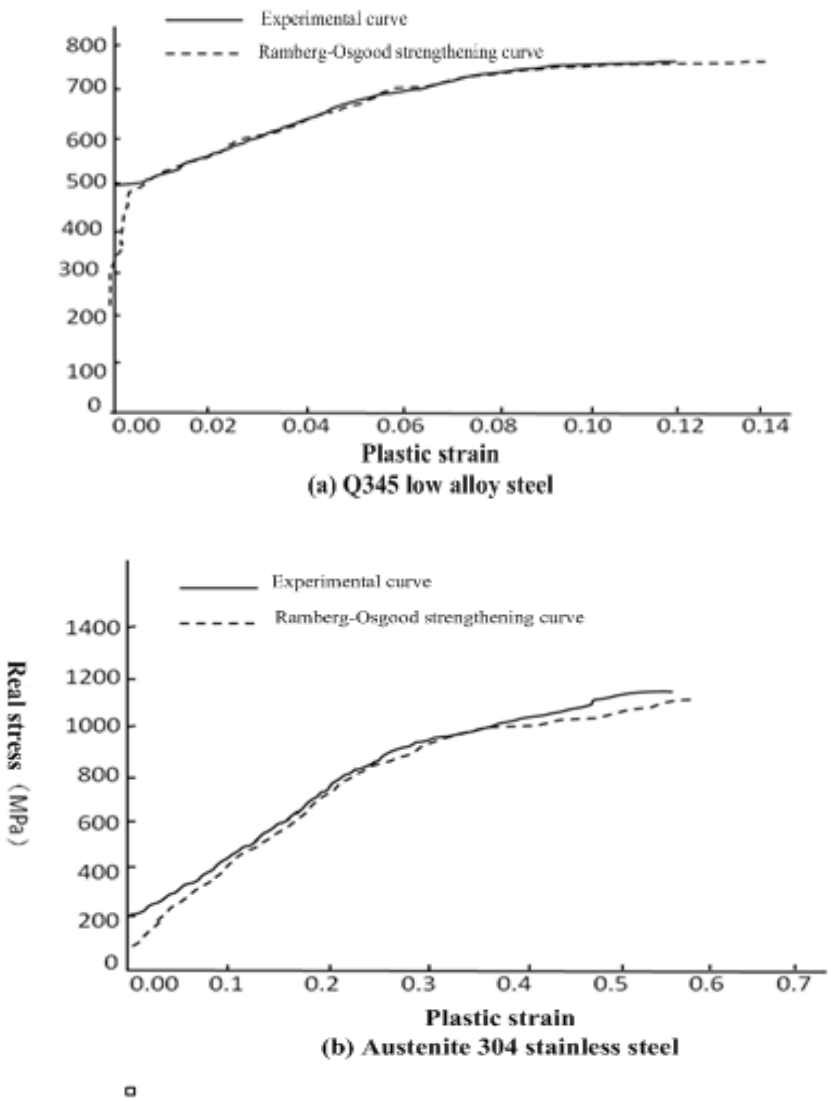
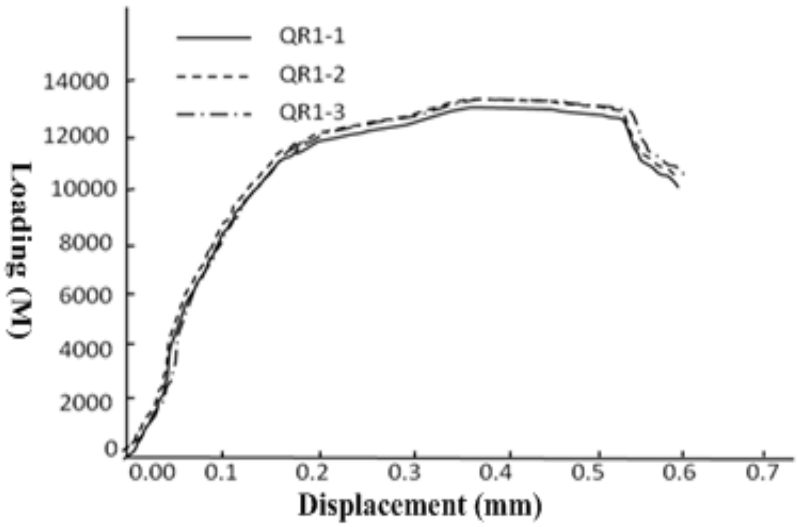



Figure 3. Relationship between real stress and plastic strain of steels

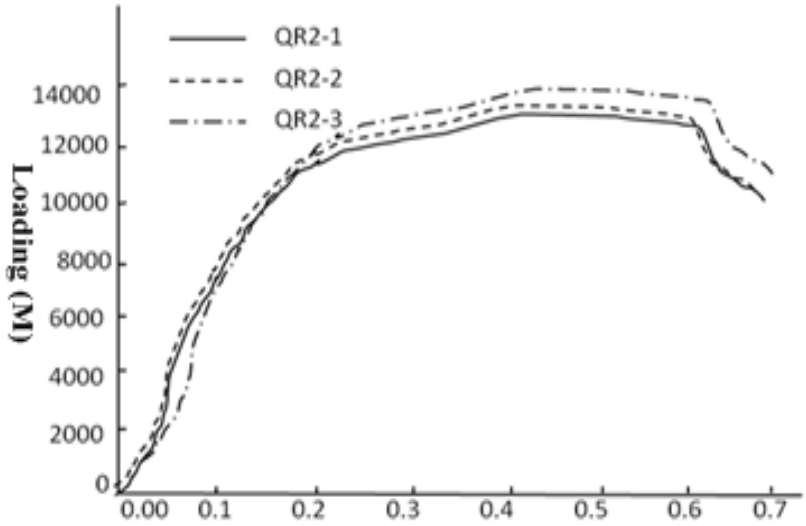
In this study, stress-strain relationship is demonstrated by Ramberg-Osgood curve which is applied the most widely. The fitting condition with measured data can be seen in figure 3. We can see a better fitting of Ramberg-Osgood model with real stress-strain curve of Q345, but due to high stress strengthening, that model cannot fit well with austenite 304 stainless steel.

**4.2 Results of notched round bar test**

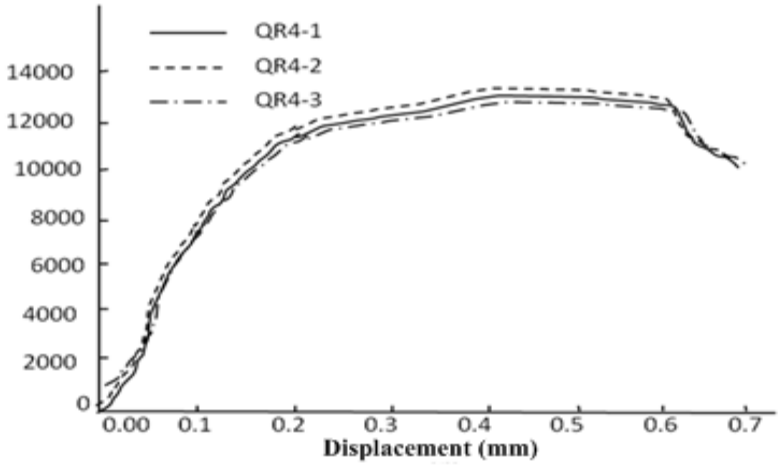
Results of notched round bar test is considered as the basis determining GTN damage parameters of two materials and also can be used to prove the predictive ability of GTN model on crack of ductile steel. Thus we perform uniaxial tensile test on three different notched round bar specimens made up of two kinds of steels respectively and obtained loading displacement curve shown in figure 4. Sudden change of slope of declining curve in the figure indicates the occurrence of ductile crack. Figure 4 suggests that, except for SR1, measured curve of other specimens disperse slightly. Thus we had better take middle curve of specimen as standard, when identifying GTN damage parameters.



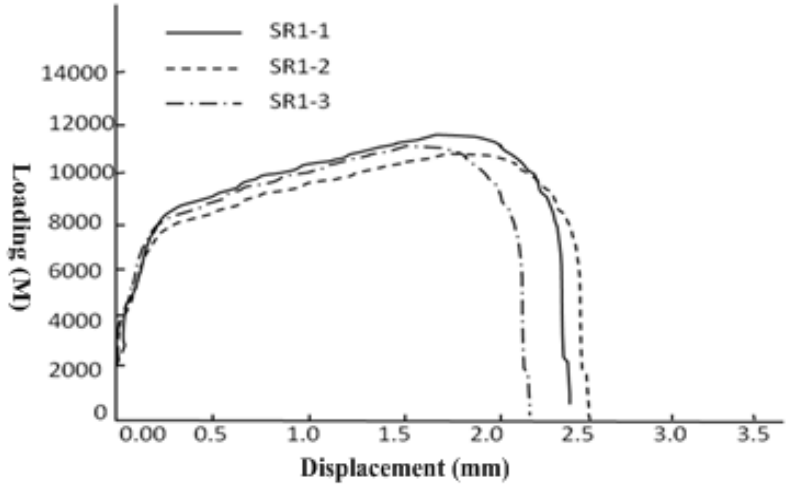

(a) QR 1 Specimen



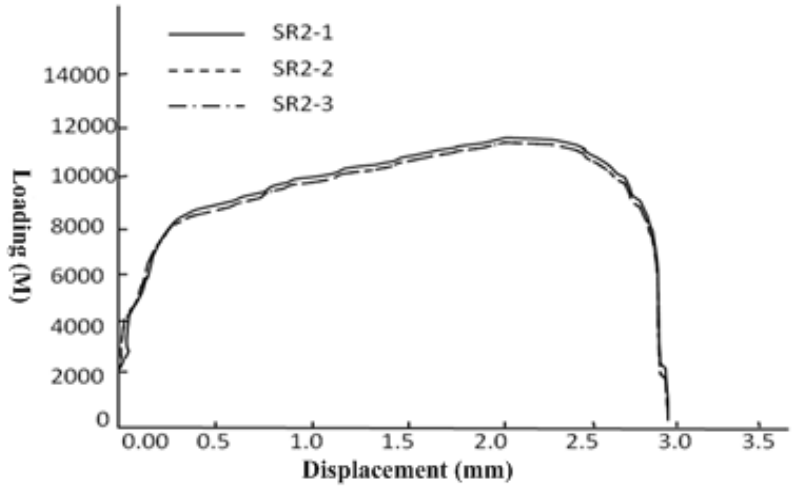

(b) QR 2 Specimen




(c) QR 4 Specimen




(d) QR 1 Specimen




(e) QR 2 Specimen

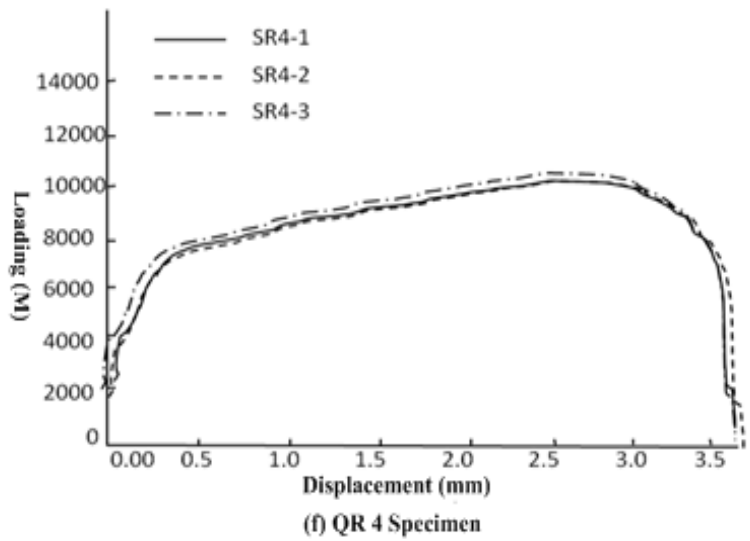



Figure 4. Loading displacement curve of notched round bar specimen

In GTN model, mechanical performance parameters and damage parameters of materials should be defined. Mechanical performance parameters have been obtained through test while damage parameters cannot be determined through relative test. Regarding these damage parameters as adjustable parameters and promoting the coincidence of load - displacement curve obtained by numerical simulation and results measured in test by adjusting these parameters, many scholars believe that, values of these parameters reflect damage evolution rule of practical materials [18].

## 5. Conclusion

This study made fracture prediction of notched round bar specimen using GTN damage model and obtained relatively satisfactory effects. For fracture prediction of steel connections, an exploratory study made has proved the feasibility of predicting fracture of connections with GTN model and impact of damage parameters on connection fracture has been initially confirmed. However, achievements obtained in this study still have a gap with accurate results due to insufficient test data and narrow samples.

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