It is not easy to simulate a real butt weld, because there are three different materials, base metal, HAZ and weld metal. A they are connected in series, the strength of a butt weld is controlled by all of the materials. In the whole loading process, the weakest component will yield first, then start to harden. Whether the other two parts will yield or not depends on their yield strength and the hardening characteristic of the weakest part. Hence in order to simulate the butt weld accurately, it is necessary to acquire the true stress–strain relationship before and after necking of each material and to dictate the load–deformation curve and ultimate load-carrying capacity of the butt weld specimen. For weld metal and base metal, coupontests represent an effective and common approach to calibrate their material model. Before necking, the following formula (Equation 1) can be used as their constitutive model because the strain in the whole specimen is almost the same. 【 】where , ， and  are the nominal strain, nominal stress, true strain and true stress, respectively

The tension necking response has been well studied in literature (Bridgman, 1952). Kolwankar et al. (2017) introduced strain distribution within the entire specimen throughout the whole loading process using Abaqus. In the present authors’ tests, a digital imaged correlation (DIC) (Costa et al., 2015) measuring system was used to detect the real strain distribution of a round bar before and after necking. For example, in the case of the ‘all-weld’ round bar of the filler metal UM1, Figures 4(a), 4(b), 4(c) and 4(d) display the measured strain distribution at some vital loading steps, the longitudinal strain distribution along the central line, the change in strain at several points along the loading process and the load tendency with the loading time, respectively. Four stages in the whole loading process: elastic, yielding, hardening and necking phases are shown in Figure 4(d). After an initial elastic phase, the steel bar began to suffer yielding. Time A is a boundary point when the weakest part yielded first (shown in Figure 4(b)) because the material is not uniform. Owing to material strain hardening, the weakest part became stronger, until the new weakest part yielded. At time B, all of the material within gauge length reached the yield strain. Then the specimen went into hardening phase. During this phase, the bar was strained homogeneously in each section even though the stress was increasing due to material strain hardening (shown in Figure 4(b) time E). The initiation of necking occurred at the point of the peak load, at time C. At the peak point in the nominal stress plotted against strain curve, the well-known Considere (1885) criterion can be established【】implying that when the true stress equals to the slope of the tangent to the true stress–strain curve, the specimen reaches the ultimate load. Equation 2 indicates an instability, such that

after this criterion is satisfied, an imperfection (e.g. a crosssection with smaller area) results in an increase of strain at this cross-section with an accompanying decrease in force, leading to a softening response (Figure 4(a) time F). During the necking phase, the increase of strain mainly occurs in the necking part, meanwhile the elastic strain unloading occurs in other parts (Figure 4(c)), which results in the strain distribution no longer being uniform in the longitudinal direction (Figure 4(b) time F), which causes a triaxial stress state in the necking area and Equation 1 is no longer useful. An accurate, true stress–strain relationship after necking cannot be calibrated using traditional analytical methods as the true stress measured is no longer uniaxial. The DIC measuring system can only record the true strain of the detected part in the whole loading process, so even then the true stress after necking cannot be calculated. Accurate calibration of material constitutive models presents many challenges, which has been identified previously by Obrzud et al. (2009). Matic (1988) and Khoo et al. (2002) determined the true stress against true strain relationship after the peak load by trial and error method. The true stress against true strain relationship was adjusted until the numerical simulation agreed with the load–deformation data of the coupon test. Smith et al. (2017) calibrated the constitutive model for cyclic loading. In this paper, the trial and error method is adopted to calibrate the Ramberg–Osgood constitutive model for base metal, weld metal and HAZ, as shown in Figure 5.

First, the coupon test needs to be conducted and then Equation 1 can be used to obtain the true stress–strain before necking. Second, according to the Ramberg–Osgood model, an improved function based on the power law stress–strainrelationship is used.【 for   for  】where εp 0 is the plastic strain at the end of the yield plateau,

σ0 is the true stress at the end of the yield plateau, if there is no obvious plateau, then suppose the point of (εp 0 , σ0) is equal to the intersection point between the test curve and σ=Eεp σ is the true stress and εp is the plastic strain, σy is the yield stress, K is a constant and n is the strain hardening exponent. Derived from Equation 3【 for 】At the peak point (εp u , σu) in the nominal stress plotted against strain curves 【】and comparing Equation 3 with Equation 5, the following equation can be obtained. Thus the initial values of the parameters can be found.【】Third, the specimen with the same geometry is simulated using the material model obtained from the last step. Fourth, the load–displacement responses are compared between the simulation result and the test result and the values of K and n are modified. Then the third step and the fourth step should be repeated until the error between the simulation result and the test result is within the tolerance limits defined. From the four steps mentioned above, constitutive model parameters of base metal and filler metal can be obtained.

For

HAZ, because of the varied mechanical properties and nonuniform microstructure within the sub-zones, a unique material parameter set is assumed for the whole HAZ in order to simplify the analysis. The method to calibrate the material model for the HAZ is almost the same as for the base metal, only the load–displacement response is used from the butt weld test. The finite-element model for calibrating the constitutive model is displayed in Figure 6. For base metal, as the specimen is symmetrical in three directions, in order to refine the mesh and perform the calculation more quickly, only one-eighth of the specimen is modelled. The model was composed of C3D8R elements with reduced integration. A mesh size of 0·5 mm was chosen after comparing the different element size, which is sufficient to capture the geometry changes and strain gradients associated with necking. For a round bar specimen of filler metal, the model was composed of axisymmetric elements (CAX8R) with reduced integration, as shown in Figure 6(b). For the HAZ, the whole butt weld specimen was modelled with three materials (base metal, weld zone and HAZ). As the specimen is symmetrical in two directions, the model is only one-quarter of the butt weld. The mesh and boundary conditions for the different materials are also shown in Figure 6.