Other dimensions are shown in Fig. 1a. Random variables that affect system resistance, including material and geometric nonlinearity, initial geometric imperfections and model error are considered in each model. Model error is defined as the ratio of the capacity of the FEA model to actual capacity. The structure reliability of CFST trusses is analyzed by introducing FORM, in order to obtain suitable system resistance factors (ϕ_s) for system-based design.

Table 1 Dimensions of the CFST truss specimen

Label	Chord	L_0 (mm)	h_i (mm)	b_i (mm)	$D \times t_s$ (mm)	ξ	Failure mode
T8	CFST	4800	375	432	140×4	1.00	Bending failure

2 Advanced analysis model

The numerical model of CFST truss with flexural behaviour is established by using the FEA package in ABAQUS. Geometric data, material properties, element selection, interface and boundary conditions are consistent with previous experiments (Han et al., 2015; He, 2012; Hou et al., 2017; Xu et al., 2014). The truss specimen was transversely loaded under the four-point flexural testing. Different FEA models of CFST truss are validated with those reported tests, and specimens T8-1 and T8-2 are chosen as the FEA model in this study for reliability analysis. This model is firstly developed to verify the load-displacement (P - u_m) curves (shown in Fig. 2a) and failure mode (shown in Fig. 2b) with previous tests, and reasonable predictions are then used for further analysis. The verified FEA models are then modified with uncertainties include the thickness of steel tubes, material properties of steel and concrete, initial steel imperfections and initial concrete imperfections for reliability analysis.

3 Reliability-based evaluation method

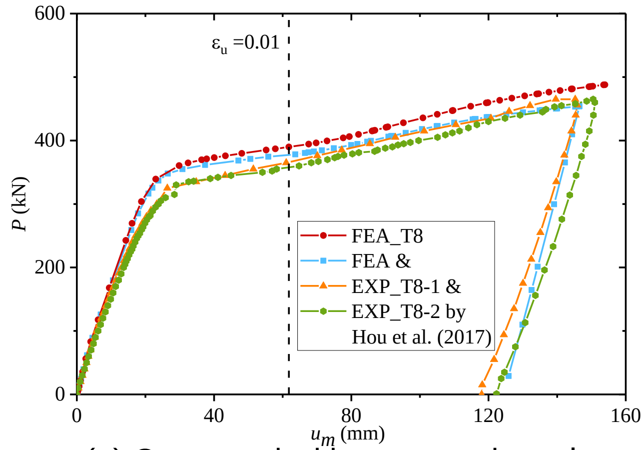
Structural reliability theory is used to study the effects of uncertainties in CFST truss structural performance. Uncertainties include material properties, geometric configurations, model errors and load variables, and statistics of which are determined by experimental or construction experiences.

3.1 Limit state equation

The limit state equation is related to one (possible) failure model of the CFST truss structure. As mentioned before, the overall bending failure can be observed in both experimental and FEA models, so the limit state equation for reliability analysis is as follows:

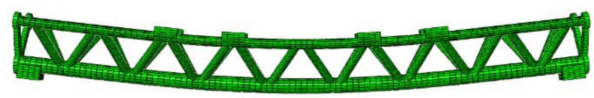
$$g = ME \cdot R - D - L \tag{2}$$

where *ME* is the model error variables (Beck et al., 2009; Han et al., 2011; Han et al., 2005). *R* represents the resistance model, *D* is the dead load and *L* is the live load.



(a) Compared with measured results

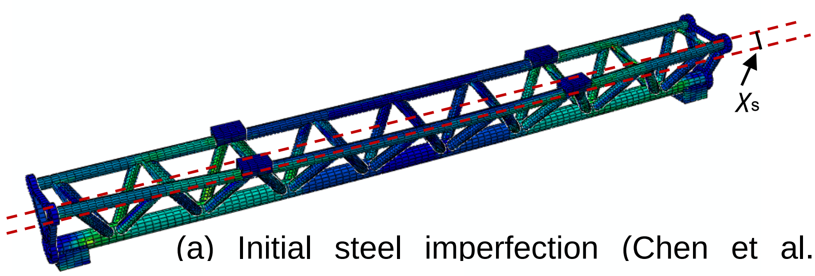
(b1) Observed in Hou et al. (2017)



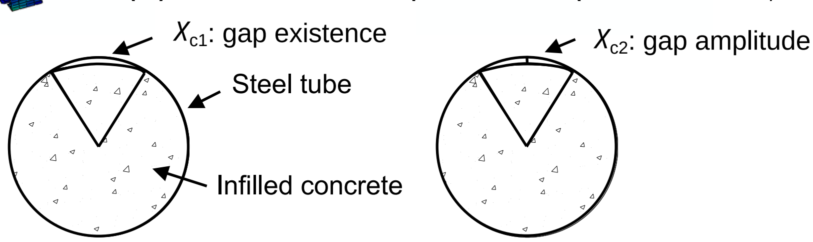
(b2) Predicted

(b) Typical failure mode

Fig. 2 Comparison of the measured and predicted behaviour of specimen T8



(a) Initial steel imperfection (Chen et al.,



(b) Initial concrete imperfection (F. Y. Liao et al.,

Fig. 3 Initial imperfections in CFST truss

3.2 Resistance variables

The uncertainties related to resistance variables include elastic modulus of steel (E_s), the yield strength of steel (f_y), the thickness of steel (t_s), the compression strength of concrete ($f_c^{'}$), initial steel imperfection (χ_s) and initial concrete imperfection (χ_{c1}, χ_{c2}). Initial steel imperfections (shown in Fig. 3a) are because steel components are not completely straight during the manufacturing and installation process, and may affect the load-carrying capacity of a steel structure to a large extent. The initial concrete imperfection (shown in Fig. 3b) that may occur during the construction of core concrete pump into steel chords and the existence may influence material interaction, sectional strength and structural stability according to precious researches (F.-Y. Liao et al., 2013). Detailed calculation of statistics of initial imperfections can be found in Chen et al. (2019). Finally, the FEA models are established with the random resistance variables considered above. Statistics of variables are obtained from the literature in this paper (Chen et al., 2019; Ellingwood et al., 1980; Lundberg & Galambos, 1996).

3.3 Load variables

A combination of dead load D_n and live load L_n are considered in order to evaluate the reliability of CFST truss under flexural behaviour. The probability for structural dead load (D_n) is assumed to be normally distributed, and the statistics of mean-to-nominal value is 1.03 with a COV of 0.08. The structural live load considering traffic load on the bridge can also be fitted as a normal distribution with the mean-to-nominal value as 1.29 and the COV as 0.18 (Ellingwood et al., 1982; Eom & Nowak, 2001). The design value of the load is given by the factored combination, as follows:

$$\phi_s R_n = \gamma_D D_n + \gamma_L L_n \quad (3)$$

The load combination obtained from AASHTO (2012) at Strength *I* limit state for normal vehicular bridge design without wind load gives γ_D = 1.25 and γ_L = 1.75. Eq. (3) is solved with a fixed load ratio L_n/D_n where six values are considered in this paper: L_n/D_n = {0.5;1.0;1.5;2.0;3.0;5.0}.

4 Reliability analysis results

The ultimate strength is obtained by MC simulations combined with advanced analysis, and the system resistance factor ϕ_s is determined for CFST truss under flexural behaviour. To determine the system resistance factor, reliability analysis, which considered random variables, is carried out after that. It also provides a suitable system resistance factor for the system-based design of CFST truss. The uncertainties applied to FEA models are extracted either from previous studies or on-site measurements. The random combination of the value includes geometric and material nonlinearity, initial imperfections and model error are generated from *MATLAB*. The FEA models are modified using *PYTHON*. Reliability analysis and evaluation are also carried out in *MATLAB*. 60 FEA models for the selected cross-sectional confinement factor ξ are analyzed, and the corresponding ultimate strength is determined when the strain of the bottom steel chord reaches ε_u= 0.01 (Han et al., 2015). The probability models of the ultimate strength factor λ (defined in Eq. 4) for CFST trusses, the distribution type, the mean and the standard deviation, are shown in Fig. 4.

$$\lambda = \frac{P_{ui}}{P_{uo}} \tag{4}$$

where P_{ui} is the ultimate strength of the CFST truss under flexural loading with random variables considered, and P_{uo} is the ultimate strength of the CFST truss without random variables.

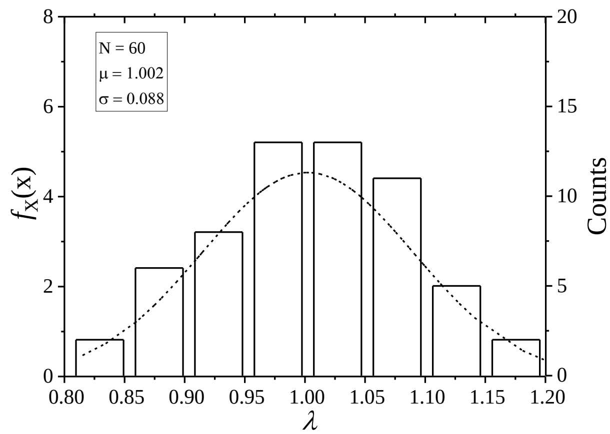


Fig. 4 Statistics of the ultimate strength of CFST trusses with ξ = 1.00

Using the reliability analysis method outlined in section 3, the reliability index of CFST truss under flexural behaviour is calculated. The relationship between the resistance factors ϕ_s and the reliability index β with different live-to-dead load ratio L_n/D_n = {0.5;1.0;1.5;2.0;3.0;5.0} are shown in Fig. 5. The reliability index β decreases with the increase of resistance factor ϕ_s. Also, the reliability index β with larger live-to-dead load ratio is smaller under the same resistance factor ϕ_s, because the traffic live load has more variability than the dead load. Based on Fig. 5, the system resistance factors ϕ_s for a specific target reliability β is then calculated as the addition of each weighted resistance factor. The average value of ϕ_s is 1.05 for a target reliability index β = 3.5, and is reduced to 0.93 for β = 4.0 for a selected CFST truss with ξ = 1.0.

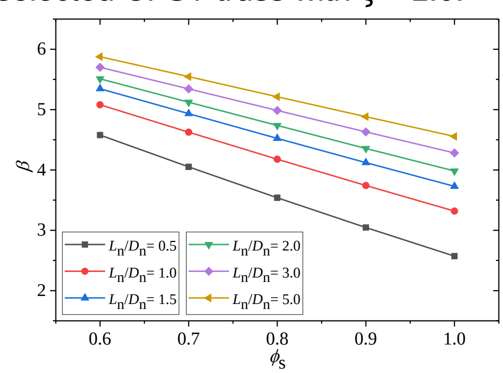


Fig. 5 The β – ϕ_s curves for CFST trusses with ξ = 1.00

5 Conclusion

The reliability-based evaluation for concrete-filled steel tubular (CFST) truss with flexural behaviour is presented in this paper. The structural behaviour is analyzed and validated using advanced nonlinear finite element analysis (FEA) method. The uncertainties related to resistance variables include elastic modulus of steel (E_s), the yield strength of steel (f_y), the thickness of steel (t_s), the compression strength of concrete ($f_c^{'}$), initial steel imperfection (χ_s) and initial concrete imperfection (χ_{c1}, χ_{c2}) are discussed. The limit state equation for the overall bending failure is solved with a fixed load ratio L_n/D_n where six values are considered: L_n/D_n = {0.5;1.0;1.5;2.0;3.0;5.0}.The system reliability analysis is carried out using First-Order Reliability Method (FORM) combined with Monte Carlo (MC) simulation and Latin Hypercube sampling (LHS) technique. The ultimate strength is obtained by advanced analysis, and the system resistance factor ϕ_s is determined. The average value of ϕ_s is 1.05 for a target reliability index β = 3.5, and 0.93 for β = 4.0 for a selected CFST truss with confinement ratio ξ = 1.0.

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