Validation of Computational Models of Steel Slag Used as Large Particles in Concrete Beams

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Abstract: Using slag in construction is a promisingly research direction for sustainable development in Vietnam. The properties of slag are expected to replaceable large particles in concretes. The article discusses the process of validating computational models of concrete beams in which large particles is replaced by steel slag. The model evaluation was conducted on the basis of experimental results and covers the process of modeling and identification of parameters in the model. The modeling and analysis is conducted in supported environment of Abaqus. Two models of stress-strain relationship of concretes are chosen for consideration in beams modeling processes. Each model has two curves representing behaviors in both stages of concretes. Concretes material is simulated both compression and tension processes. They are combined with two steel reinforcement models to find suitable models of slag concretes. A meshed size is also proposed for the beams modeling. Small errors between two relationship curves of load and mid-span deflection indicates that the validation is successes.

Key words: steel-slag, concrete beams, validation, Abaqus.

1. Introduction

Reinforced concrete using steel slag is to reduce polluted environment. It is a topic of the current researches in Vietnam. Steel slag is a waste product from steel factories and non-stop increase volume in Vietnam. Researchers think that it should be used in construction parts. Steel slag is considered as materials alternative of rocks in concrete. There are several researches for slag material in reinforced concrete, which is composed of experimental and simulation methods. Experimental method could show the real value of the load carrying, volume, stiffness, total deformation. Meanwhile, the development of simulation methods using finite element method could clarify behavior of structural materials under loads. Simulation methods are popular and widely developed in recent years with the support of some software such as ANSYS, DIANA, and ABAQUS. The paper uses ABAQUS [4] software for calculations of reinforced concrete beams.

Three-point flexure testing of the reinforced concrete beams having slag have been done in the laboratory of the UTE (HoChiMinh City University of Technical and Education). The reinforced concrete beam, in which have steel slags, is hereafter named as SRCB. It is known that computational simulation methods help reducing fund of experiments. Simulation methods are flexible to adapt changing experiments and also intuitive than empirical methods. So it needs a validated simulation model of SRCB for further development related to current topic.

Besides, the simulation calculations needs to manage all components that can affect the accuracy of the model such as concrete material model, the model of the steel material, the model of contact between two different materials. The size elements and boundary conditions also affect the analysis results. Success models of concrete and steel reinforce will be used and validated in the paper.

2. Experimental test of slag reinforced concrete beam

SRCB is conducted 3-point flexure test as shown in Fig. 3, under the effect of compressive force to the speed 0.05KN/sec until the vandalism. In the process of the experiment, the LVDTs (Linear Variable Differential Transformers) are installed at locations of 1/4 and 1/2 girder spans for measuring displacement. Strain gage is attached at 1/4 beams length for deformation measurement. The total length of the beams is 3300mm. The cross section is 300x200mm. Reinforcement in the beams is shown in Fig. 1. Five longitudinal reinforcement of 14mm dia. are arranged at the bottom of beam, and two longitudinal reinforcement of 12 dia. are arranged at the top layer of beam. Shear reinforcement uses 6 dia. at 150 center-to-center. Reinforced protective layer is 25mm.

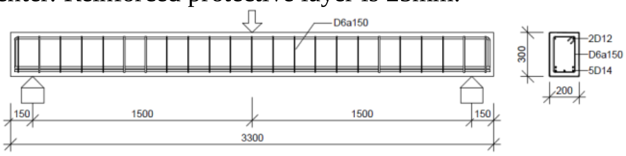

Fig.1 Elevation layout of reinforcement in beam and cross-section

Fig.2. Bending test of beams.

Table 1 shows a summary of mixture ratio using in SRCB. This ratio of mixture is for concrete grade of 40MPa.

Table 1 Mixture ratio of concrete using steel slag

Cement (kg)	Sand (kg)	Steel slag (kg)	Water (l)	Water / Cement	Additives (ml)
411.7	687.1	1431.3	190	0.46	4.1

3. Computational models

The process of validation estimates the degree of similarity between the computational model and the real word. Several chosen elements are applied and discussed to find out the best model. Different model for behavior of concrete, different model for behavior of reinforced steel, and preliminary verification of the model with parameters having a significant influence on the work of model are consider in the following paragraphs [9].

3.1 Models of concrete material

There are two models selected for concrete material that are Hsu - Hsu (1994) models [6] and Hognestad models (1951) [7].

3.1.1 *Models of Hsu and Hsu*

The stress-strain curve for concrete under compression and tension obtained from the experimentally verified numerical method by Hsu and Hsu [1].

The model is presented in Fig. 3. Eq. (1) is used to calculate the compressive stress values (σ_c) in the softening curve of concrete material.

$$\sigma_c = \left(\frac{\beta \left(\varepsilon_c / \varepsilon_0 \right)}{\beta - 1 + \left(\varepsilon_c / \varepsilon_0 \right)} \right) \tag{1}$$

where ε_c is compressive stress which depends on σ_c , in curve of stress-strain relationship. The parameter β and the train at peak stress ε_0 are given in Eq. (2) and Eq. (3), respectively.

$$\beta = \frac{1}{1 - \left(\sigma_{cu} / \varepsilon_0 E_0 \right)} \tag{2}$$

$$\varepsilon_0 = 1.291 \times 10^{-5} \sigma_{cu} + 2.114 \times 10^{-3} \tag{3}$$

Modulus E_0 is given by Eq. (4). The ε_d is train at $\sigma_c = 0.8\sigma_{cu}$.

$$E_0 = 1.8 \times 10^2 \sigma_{cu} + 3.28312 \times 10^3 \tag{4}$$

The stress-strain relationships for concrete under tension are assembled by linearly portions as presented in Fig. 3. Where, σ_{t0} is maximum tensile stress at critical tensile strain ε_{cr} .

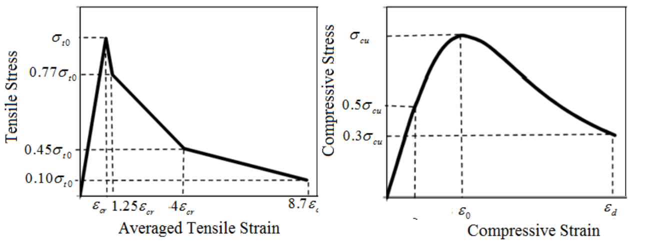

Fig.3 Stress-strain curve for concrete under tension and compression (Hsu – Hsu)

3.1.2 *Models of E.Hognestad*

The models of E.Hognestad are presented in Fig. 4. Stress-strain curve for concrete under compression is a constitutive model. The relationship of axial compression stress and strain is expressed in Eq. (5).

$$\sigma_c = \left| \begin{array}{l} f_c \left(2.\, \varepsilon / \varepsilon_0 + \left(\varepsilon / \varepsilon_0 \right)^2 \right) \\ f_c \left(1 - 0.15 \dfrac{\varepsilon - \varepsilon_0}{\varepsilon_u - \varepsilon_0} \right) \end{array} \right. \tag{5}$$

where f_c is uniaxial compressive strength of concrete, ε_0 is yield strain, and ε_u is ultimate strain.

Constitutive model for unidirectional tensile is expressed in Eq. (6).

$$\sigma_t = \left| \begin{array}{l} f_t \left(1.2\, \varepsilon / \varepsilon_t + 0.2 \left(\varepsilon / \varepsilon_t \right)^6 \right) \\ f_c \left(\dfrac{\varepsilon / \varepsilon_t}{\alpha_t \left(\varepsilon / \varepsilon_t - 1 \right)^{1.7} + \varepsilon / \varepsilon_t} \right) \end{array} \right. \tag{6}$$

where, f_t is uniaxial tension strength of concrete, and ε_t is concrete tensile strain at peak of the curve.

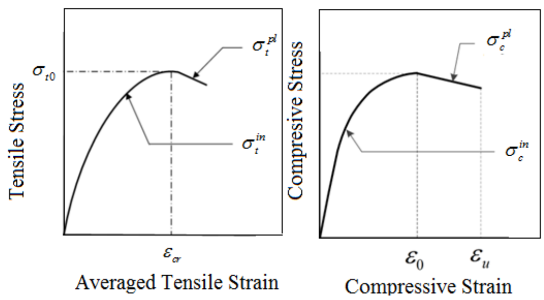

Fig.4 Stress-strain curve for concrete under tension and compression (E.Hognestad)

3.2 Models of steel reinforcement material

The models of steel reinforcement are needed in ABAQUS environment. Two different steel material models are applied. Each model is assumed in both stages of steel material. They are elastic and plastic behavior. The first model used a simple elasto-plastic law. The second model is an improvement of simple elasto-plastic law.

3.2.1 *Simple elasto-plastic law (SEPL)*
SEPL was defined by a curve of stress-strain relationship, as showed in Fig. 5. The curve is fully defined by the *Young's* modulus E_s , a standard value of steel reinforcement, and the tensile yield strength f_y .

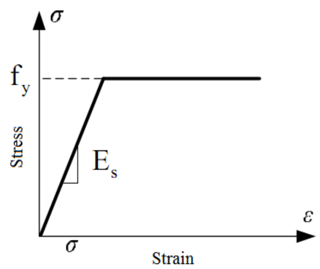

Fig. 5 Elasto-plastic constitutive law of reinforcement

3.2.2 *Improvement of a simple elasto-plastic law (IEPL).*
The second model is an improvement of simple elasto-plastic law. The curve of stress-strain relationship is defined by the *Young's* modulus, the tensile yield strength f_y and the tensile critical strength f_u . Model has been successfully applied by number authors such as Ngo and Scordelis, Vebo and Ghali [3].

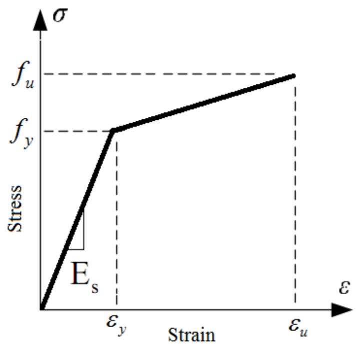

Fig. 6 Improvement of elasto-plastic constitutive law of reinforcement

4. Simulation

A concrete beam is modeled in the form of solid elements. The material required parameters for non-linear analysis are presented in Table 2. In ABAQUS environment, the elements named as C3D8R [5] are used for concrete material models. The choice of the wire form is applied for the reinforced bars. The reinforcing bars are worked together with concrete by embedded method.

Table 2 The parameters for non-linear analysis

Concrete	E_c [Mpa]	υ_c	f_c [Mpa]	f_t [Mpa]	E_c [Mpa]
	40.4	0.2	40.86	3.97	40.4
Steel	E_s [Mpa]	υ	f_y [Mpa]	f_u [Mpa]	E_s [Mpa]
	210	0.3	365	420	210
Other parameters	K_c	ε	σ_b/σ_c	ψ	μ
	0.667	0.1	1.16	30^0	0.00005

Fig. 7 shows a model of SRCB in 3-point flexure testing simulation. Load is applied using displacement control method. Analysis result is presented in Fig. 8.

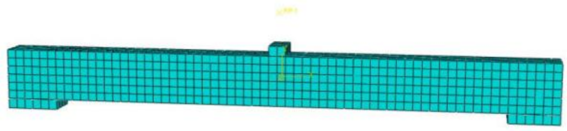

Fig. 7 Model of SRCB

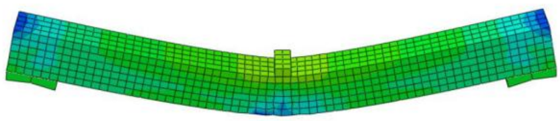

Fig. 8 Result of calculation

5. Mesh size

The mesh size affects to convergence, and results of analysis. Suitable elements sizes are selected so that they do not affect to analysis results. Several elements sizes used for exploration. They include element size of 200mm (Mesh-200), element size of 100 (Mesh-100), element size of 80 (Mesh-80), element size of 50 (Mesh-50), and element size of 20 (Mesh-20). The analyze results of different element sizes are presented in the Table 3.

In the table, mid-span deflection is d. P_m, P_t are flexural load of simulation and test, respectively. Total measurement time spent for an analysis is of CPU Intel core i7 (3.2GHz).

Table 3 Results for beam for different mesh sizes

d (mm)	Mesh sizes 200	Mesh sizes 100	Mesh sizes 80	Mesh sizes 50	Mesh sizes 20	Test
	P_m (kN)	P_m (kN)	P_m (kN)	P_m (kN)	P_m (kN)	P_t (kN)
0.01	42.5	80.1	74	69.8	70.1	72
0.015	63.2	93.2	96.2	97.8	98.2	100.8
0.018	64.4	100.7	98.4	99.1	99.8	110.2
0.02	67.5	114.7	113.6	114.2	114.4	115
0.025	71.4	112.9	115.7	116.4	117.2	119
0.03	73.2	114.9	118.6	119.2	119.4	120.2
0.035	42.5	80.1	74	69.8	70.1	72
Time (min)	15.3	30.43	51.2	162.05	216.1	Time (min)

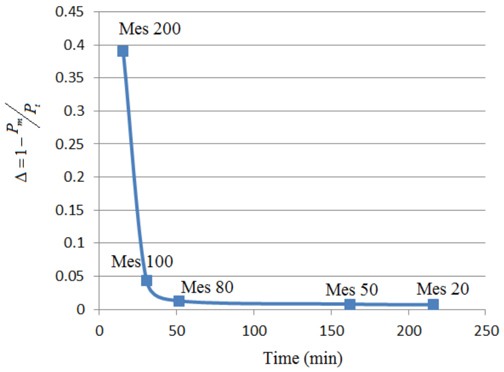

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Fig. 9. Value comparision chart of mesh sizes in 0.03 of value of mid-span deflection

A deviation parameter $\Delta = 1 - {P_m}/{P_t}$ is defined to explore the exact ratio of analysis load corresponding to a certain mid-span deflection. The relationship of deviation parameter and total analysis time corresponding to mid-span deflection value of 0.03m is drawn in Figures 9.

Figures 9 shows deviation parameter decreased, but analysis time increased as meshed sizes decreased. Based on the figure, Mesh-80 is recommended for simulation of SRCB.

6. Validation and discussion

The validation process is performed through comparison of several cases, which are based on the combinations of two models of concrete and two models of steel. The first is conducted on IEPL model. Fig. 10 shows the mid-span deflections increased with load. Two concrete material models mentioned above combined with the IEPL model of steel reinforcement are represented by discontinuous lines. Test results are represented by a continuous line. The combination of IEPL model and Hsu - Hsu models is STAGE-1. The combination of IEPL model and E.Hognestad model is STAGE-2.

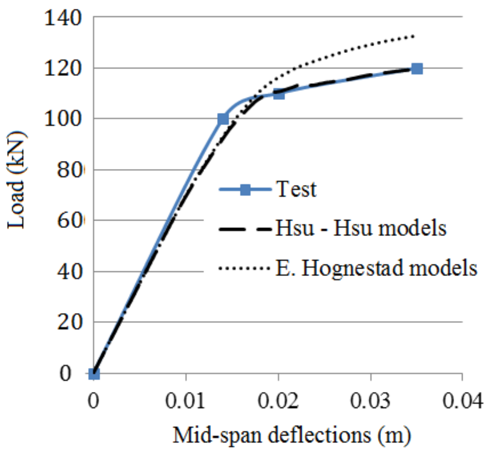

Fig. 10 Mid–span deflections versus loading of STAGE-1, 2

It could be seen in Fig. 10, the beam is in elastic stage having high stiffness and loading under 80kN. Deflections increase linearly with the increasing of load. There is no difference between the two models of concrete material. Above load of 80kN, behavior of beams is in elasto-plastic stage, mid-span deflections are accelerated with loading. Load of 120kN is the failure load of beam. E.Hognestad model shows the failure load of 132.5kN. The other model shows the failure load of 120.2kN, which is similar to experiment results. It can be seen that the Hsu-Hsu models basically consistent with the actual test results.

The second is conducted on SEPL model. The combination of SEPL model and Hsu - Hsu models is STAGE-3. Combination of SEPL model and E.Hognestad models is named as STAGE-4. Fig. 11 shows the curves of mid-span deflections versus loading.

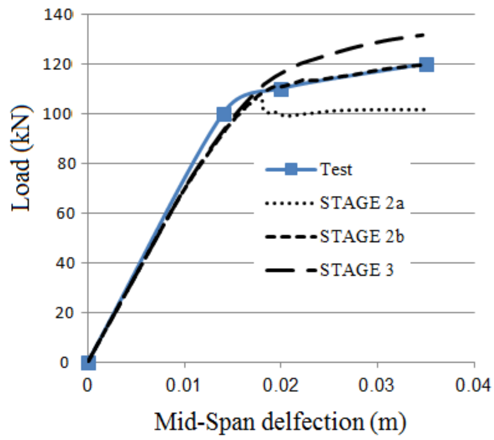

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Fig. 11 Mid–span deflections versus loading of STAGE-3, 4

STAGE-3 shows the failure load of 132.2kN. It is similar to STAGE-2. It could be said that E.Hognestad models is not influenced by steel models.

There is a drop of loading in the STAGE-4 curve. It occurs when loading reaches 110.2kN. Following, failure load of beam is 101.2kN. It might be caused by steel model. Tensile stresses in steel reaches to f_y , deformation is assumed reaching to infinity.

Analysis results show that concrete models of Hsu-Hsu combined with the IEPL of steel model could help simulate SRCB successfully. In this 3-point flexure test, the maximum error is approximately 5% corresponding to deflection of 0.015m at mid-span of beam.

6. Conclusions.

The reinforced concrete bending beams having slag is a object of simulation. Processes of development and validation computational models are presented. Reinforced concrete beams with sizes of 200x300x3300 in 3-points bending test is simulated by ABAQUS supported environment.

In simulation process, several parameters could affect the accuracy of analysis results are considered. Parameters could be listed such as concrete material model, the model of the steel material, and elements mesh size.

It is found that concrete material models proposed by Hsu-Hsu (1994) combined with a improvement of reinforcement steel material model could predict exactly testing results. Testing results mentioned is relationship of loading and deflections at mid-span. Besides, meshing size of 80mm is proposed for similar modeling of steel-concrete beams having slag.

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