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Effects of different shapes of aggregate on the behaviour of plain concrete beam at meso-scale

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Abstract

In this study, behaviour of plain concrete beam under three-point bending is simulated at meso-scale (10^{-4} -10 cm). At meso-level, concrete is assumed to consists of either a two-phase or a three-phase composite material (mortar, aggregate and/or interfacial transition zone-ITZ). First, the aggregates are generated based on a given aggregates gradation and then those are placed randomly within the concrete sample following uniform distribution. The remaining space of the concrete sample is then filled with the mortar in case of a two-phase assumption. However, in three phase modelling, a part of the mortar of finite thickness surrounding the aggregates is assumed as ITZ. In this study, three different shape of aggregates: circular, elliptical and polygonal, are considered and their effect on the simulated load deformational response of plain concrete beam is studied. The simulated results are then validated with the corresponding available experimental data. A statistical analysis based on variability of aggregates generation for three different shapes of aggregates is also performed.

Keywords: Meso-scale model, Concrete, Circular, elliptical and polygonal aggregates, Three-point bending.

1. Introduction

Concrete is one of the commonly used composite building materials in which the sand and aggregates particles are randomly distributed in a binding medium called cement paste. Since, concrete is a highly heterogeneous material, it's mechanical property is highly depending upon it's individual components (Cement matrix, sands, aggregates). In last few decades, the behaviour of concrete structures under different kinds of loading were simulated [1-3]. However, in those simulated studies, it was assumed that concrete is a homogeneous material. The variability in the mechanical properties of each of the concrete constituents could results in significant differences in the concrete behaviour and therefore the homogeneous assumption of concrete may not be reliable for analysing large-scale concrete structures [4, 5]. For example, in a study on simulation of concrete structures at high temperature, Bošnjak [6] showed that a numerical model of concrete with homogeneity assumption can simulate the temperature and pore pressure distribution quite well. However, localised failure phenomenon such as spalling cannot be captured well unless the aggregates were explicitly modelled in the numerical model of concrete.

In general, at high temperature, the volume of the aggregates increases with the increase in temperature. Whereas, the hardened cement paste surrounding the aggregate is dehydrated and as a result, it shrinks [7, 8]. After cooling, the aggregates can come back to its original shape immediately. However, same does not happen to the dehydrated cement paste. Such increase and decrease in the volume of the concrete constituents are dependent on the maximum temperature reached during an event of fire [7, 8]. Due to these expansion-contraction processes, the interfacial region between the aggregates and surrounding cement matrix (called interfacial transition zone-ITZ) in the concrete becomes the weakest zone. This interfacial zone damage first in the concrete by cracking. Also, at ambient condition, the highly heterogeneityof concrete at the micro-structure level makes the cracking processes very complex [1, 3] such that the ITZ becomes the weakest region in the concrete domain. Therefore, the meso-structure of concrete where the aggregates are explicitly modelled, plays a crucial role in the crack initiation and propagation process and consequently effects the macroscopic behaviour of concrete [4, 5].In this regard, Chen et al [9] conducted numerical study in 2D cube samples at meso-scale under uniaxial compression and tension with three different shapes of aggregates and highlighted the advantages of meso-scale sudy.

Hence, in order to capture more realistically different loadings effect on concrete structures, the homogeneous assumption of concrete may not be sufficient [10, 11]. Therefore, in this study, concrete is modelled numerically at meso-scale where aggregates are explicitly modelled. Three different shapes of the aggregates are chosen and their effect on the beam specimens in two dimensions (2D) is simulated under quasi-static three-point loading. This study is just a

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step in the direction in the prediction of the more realistic failure pattern of concrete beam under three-point bending.

2. Meso-scale model for concrete

At meso-scale, it is assumed that concrete is either a two phase or a three phase composite material consisting of mortar matrix, aggregate and/or interfacial transition zone (ITZ) which surrounds the aggregates. In this study, first the aggregates with a particular shape (either circular, elliptical or polygon) and a random size (which is uniformly distributed in each particle size rangein a standard aggregate gradation) are generated. The position of the aggregates in the concrete domain are then fixed by assuming that their position is random following uniform distribution. However, it is required to check and ensure that no two particles intersect each other. The remaining available space in the concrete domain is then assumed to consist of mortar of particular composition ina two-phase composite. On the other hand, in a three phase assumption, mortar of certain thickness around the aggregates is considered as ITZ which is the weakest zone in the concrete domain. These method of modelling concrete numerically is called Random Aggregate Model (RAM) [9, 12].

2.1 Aggregate generation and placement

In this study, aggregate of three different shapes (circular, elliptical and polygonal) are considered. These arethe steps that are being used to generate and place the aggregate particles of circular shape in a given concrete domain following a given gradation of aggregate [3] in 2D [9], (these can be used for particles of other shape):

Step-1: First, area of aggregate in each size range $[d_i,d_{i+1}]$ is evaluated, so that the area of aggregate in each size range becomes

$$A_{agg}[d_{i+1}-d_i] = \frac{P(d_{i+1})-P(d_i)}{P(d_{max})-P(d_{min})} \times P_{agg} \times A \qquad (1)$$

where, $P(d_i)$is the aggregate percentage which is smaller than diameter d_i; d_{min} and$d_{max}$are the minimum and maximum diameter of the circular aggregate in that particular gradation, $P_{agg}$is the volume of aggregate inconcrete in percentage, A is the total area of concrete.

Step-2: Starting with the segment of the aggregate gradation which has largest size particle, an aggregate is generated with a diameter d, such that:

$$d = d_i + \eta(d_{i+1}-d_i) \qquad (2)$$

where, η is a uniform random number lies between 0 and 1.

Step-3: The aggregate particle, already generated, is then positioned in a given concrete domain, such that

$$x_i = x_{i,min} + \eta(x_{i,max}-x_{i,min}) \qquad (3)$$

where, x_i is centroid of the i^{th} coordinates of the newly generated particle in the e_i Cartesian basis.

Step 4: Now, it is required to check whether the newly generated particle overlapsany of the previously generated particles or with the domain boundary.

Step-5: Steps 2-4are then repeated until the area of aggregate is not sufficient in a specific grading segment to generate one more particle in that range,

Step-6: Steps 2-5are then repeated for the next smaller grading segment of aggregate.

The above steps are written only for circular type of aggregates. Details in generation and separation check of other types of particles (eg., ellipse and polygonal) can be found in [13,14].

2.2 Constitutive models and material parameters

In this study, coupled plastic and damage based material model [9] is taken as the constitutive relation for the mortar matrix and ITZ. Through this model, the stress-strain relation is described as

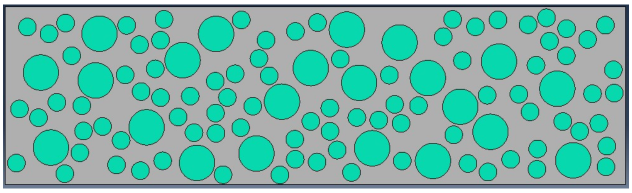
$$\begin{aligned} \boldsymbol{\sigma} &= (1-d')\boldsymbol{D}_0^{el}:(\boldsymbol{\varepsilon}-\boldsymbol{\varepsilon}^{pl}) \\ &= (1-d')\overline{\boldsymbol{\sigma}}) \end{aligned} \qquad (3)$$

where, $\boldsymbol{\sigma}$ and $\overline{\boldsymbol{\sigma}}$are the Cauchy and effective stress tensor, $d' = d'_{c/t}(\overline{\boldsymbol{\sigma}}, \boldsymbol{\varepsilon}^{pl}_{c/t})$is isotropic scalar damage variable in compressive or tensile loading, $\boldsymbol{\varepsilon}^{pl}_{c/t}$is the plastic strain tensor and$\boldsymbol{D}_0^{el}$represents initial constitutive tensors. Whereas, aggregates are assumed to behave like a linear elastic materialdue to its high strength and stiffness as compared to surroundingmortar.

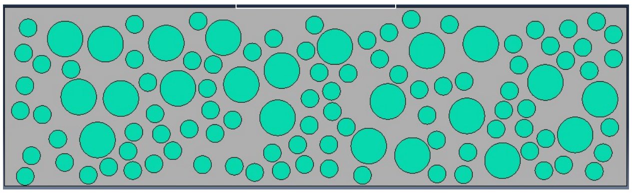
3. Results and discussion

Based on the above discussed meso-scale model of concrete, aplain concrete beam is numerically modelled and its behaviour is simulated under three-point loading. Beam specimen of depth (D) 50 mm and length (L) 175 mm is considered and its load deformation behaviour is simulated for which experimental data of load vs crack mouth opening displacement (CMOD) is available [3]. In experiment [3], relative horizontal displacement of two points located at distance D/2 from the centre of the beam is measured and reported as CMOD [3]. Details of the test and mix-proportion of concrete can be found in [3].

For the given volume fraction and gradation [3, 15], coarse aggregates are generated and placed within the beam domain. In this study, aggregates of three different shapes: circular, elliptical and random polygonal are modelled and their effect on the load-deformation behaviour of concrete beam is studied. Three such simulated configuration of a beam specimen with circular aggregates are shown in Fig. 1 in case of a two phase assumption (i.e., aggregate and mortar).



(a)



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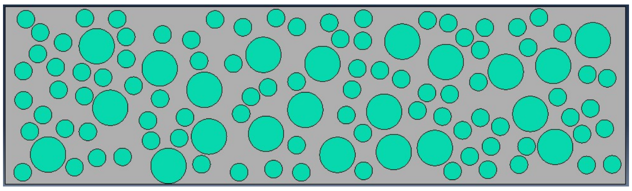


(c)

Fig. 1.(a-c).Three simulated random distribution of circular aggregates in 2D in a beam of size 175 mm x 50 mm x 50 mm

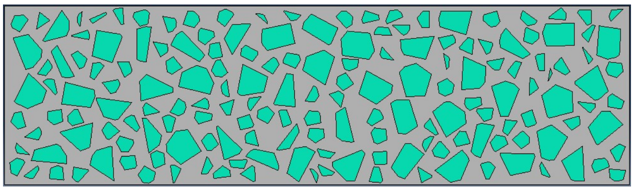


Fig. 3.Simulated random polygonal distribution of aggregates in 2D in a beam of size 175 mm x 50 mm x 50 mm

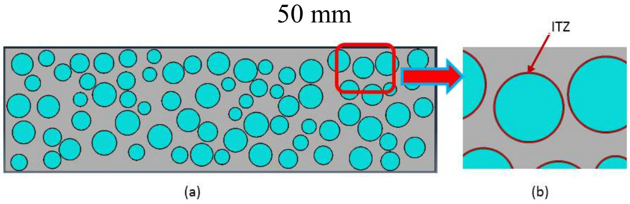


Fig. 4.(a) Simulated random distribution of circular aggregates and ITZ in 2D in a beam of size 175 mm x 50 mm x 50 mm, (b). Enlarged view of ITZ

Table-1. Material Properties

	Young's modulus [GPa]	Tensile strength [MPa]	Fracture energy [N/mm]
Aggregate	50	-	-
Mortar	30,2	5.2	0.1
ITZ	30,2	2.6	0.05

From Fig.1, different possible random arrangements of circular aggregate can be seen. Similarly, one such configuration in case of elliptical and polygonal aggregate is shown in Fig.2 and Fig.3. Whereas, Fig. 4 shows a possible simulated distribution of aggregates in the beam specimen with three phase modelling approach. Keeping in mind space constraint, only details for circular aggregate specimen it is shown. In studies [9, 16], thickness of ITZ was considered in size of 0.05 mm to 1 mm either based on nano-indentation test [16] or numerical study [9]. Therefore, in this study, ITZ is assumed to have a thickness of 0.1 mm. Also, the strength and stiffness of ITZ were taken in the range of 0.5 to 0.8 times of the mortar properties [9, 16]. So, in this study, this ratio of the strength and stiffness of ITZ to mortar is taken as 0.5.The material properties of different concrete constituents (mortar, aggregate and ITZ) are taken from [3] and some are shown in Table 1.

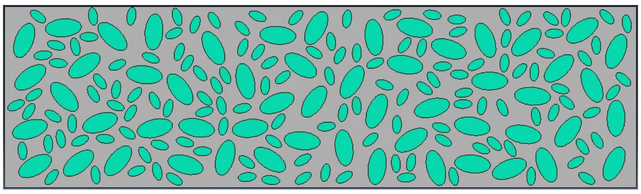


Fig. 2.Simulated random distribution of elliptical aggregates in 2D in a beam of size 175 mm x 50 mm x 50 mm

Displacement controlled loading is used in order to simulate the behaviour of concrete beam specimen. A displacement is applied at the mid-point of the beam. First, load-CMOD of the beam specimen is simulated for three different aggregate shape and is shown in Fig.5. Here, the results are plotted based on one simulated aggregate configuration of concrete beam specimen. The progressive damage pattern simulated for the specimen with circular aggregates are shown in Fig. 6 at different stage of loading. Similar damage pattern for the specimen with other two types of aggregates are shown in Fig. 7 to Fig.8 at the end of the application of mid-point displacement of 0.25 mm only for the sake of space constraint. Here, the possible crack path is shown in terms of damage variables d, whose value of 0 indicates undamaged material and 1 indicates a fully damaged portion. Since, in the simulation, the aggregate has higher strength than the surrounding mortar, the cracking path do not pass through an aggregate [Fig. 6-8]. Rather, this cracking processes follows a path which goes through mortar and mortar-aggregate interface. From Fig.5, it seems that there is very little effect of aggregate shapes in the simulated behaviour of beam under three-point loading. However, these are the response obtained form one random aggregate sample. For other random configurations of aggregate, the response could vary significantly. Therefore, it is required to check the effect of several such possible random configurations of aggregate in the behaviour of beam. This will be check next. However, before that the model results are validated with the experimental data.

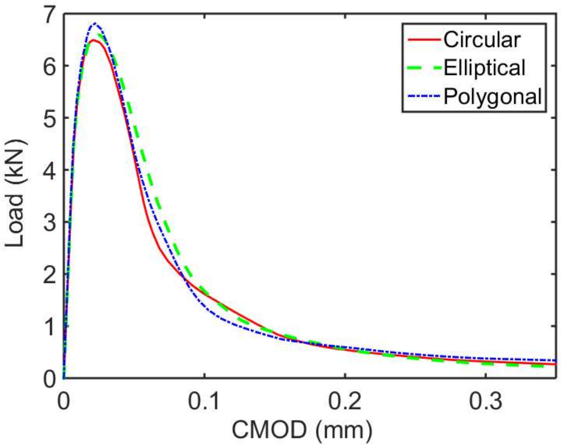
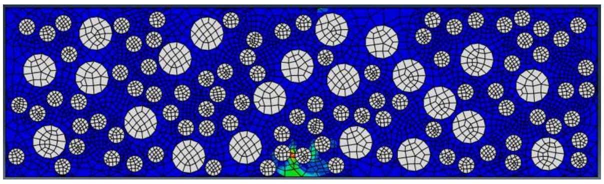
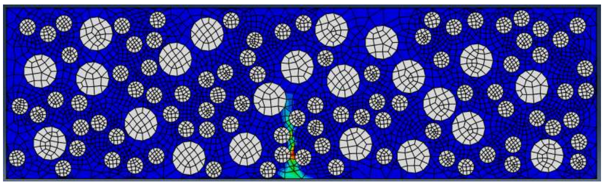


Fig. 5.Simulated load-CMOD in case of three different aggregates shapes



(a)



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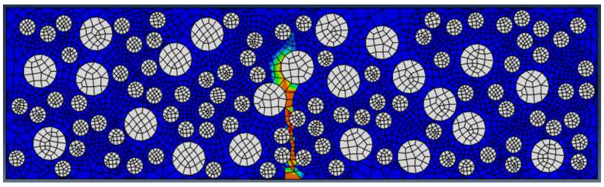

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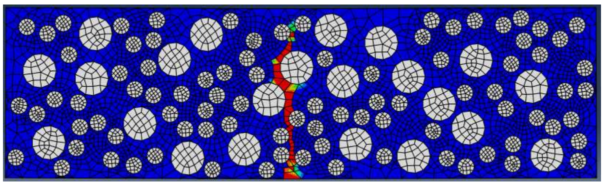

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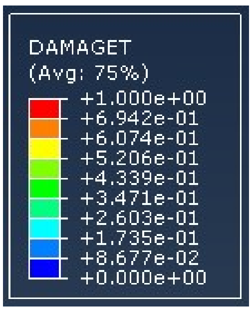

(e)

Fig. 6.Progressive damage pattern at different stage of loading after central vertical displacement of (a) 0.027 mm, (a) 0.057 mm,(a) 0.132 mm, (a) 0.25 mm,(e). tensile damage value

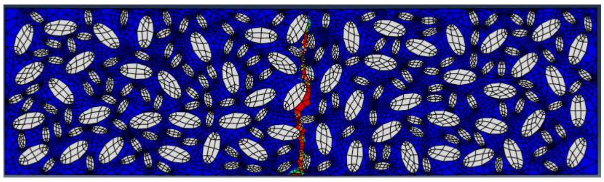

Fig. 7. Possible failure pattern under mechanical load of concrete beam after central vertical displacement of 0.25 mm with elliptical aggregates

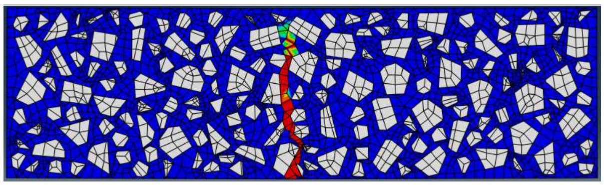

Fig. 8. Possible failure pattern under mechanical load of concrete beam after central vertical displacement of 0.25 mm with polygonal aggregates

In order to validate the model results, simulation have been run for three different types of aggregates with and without ITZ. Keeping in mind space constraint, load-CMOD responses in case of only circular shape is plotted in Fig.9 along with the experimental response [3]. From Fig. 9, it can be seen that the simulated result without considering ITZ shows much higher peak load as compared to experiment. However, with the consideration of ITZ with thickness of 0.1 mm quite well can capture experimental response. Therefore, results that are shown next onwards are based on a three-phase model i.e., with the inclusion of ITZ.

The above simulated load-CMOD (Fig. 5 and Fig. 9) and related damage pattern (Fig. 6 to Fig. 8) are shown in case of one simulated aggregate pattern i.e, for one sample. Whereas, it could be any random distribution of aggregate in real case. Hence, the load-CMOD response are generated for multiple simulated random configuration of aggregates i.e., for different number of samples. These simulations are conducted for all the three different aggregate shape.

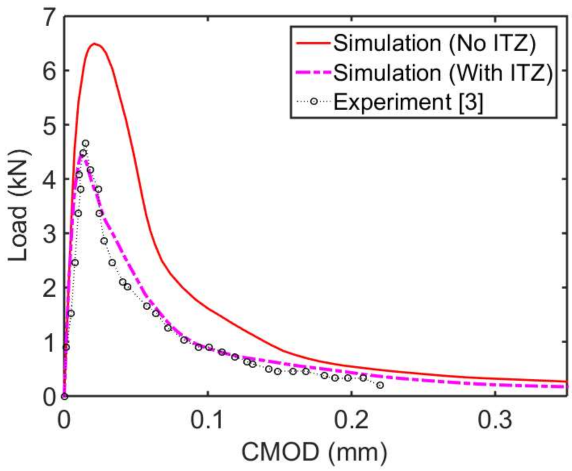

Fig. 9.Simulated load-CMOD in case of circular aggregates concrete beam with and without ITZ

Fig. 10 shows load-CMOD response of fifty number of such samples (here 50 samples are chosen for better clarity) in case of circular aggregates so that the relative variation in load at different CMOD can be observed. From Fig. 10, it can be said that the variation in load occurs mostly during peak and in post-peak region owing to the randomness lies in size and distribution of aggregates in concrete domain. Similar phenomenon happens in case of two other shapes of aggregate and can be seen in Fig. 11 and Fig.12. Instead, mean and standard deviation of the peak load with different number of such samples (i.e., for randomness in size and position of the aggregates) are shown in Fig.13-14. From Fig.13, it can be said that polygonal shape aggregate gives less peak load compared to the other two types of aggregates. These figures (Fig.13 and Fig. 14) also suggest that simulating around 50 numbers of such random samples is sufficient to get a converged peak load regardless of the shape of aggregates. However, this variation in peak load of one such simulated random concrete sample from the mean load is less than 10%.

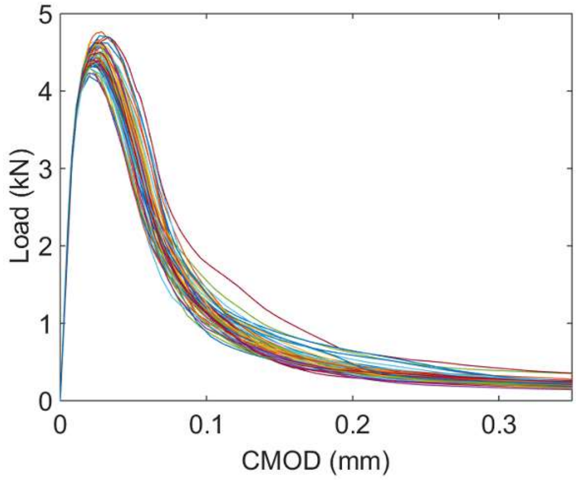

Fig. 10.Simulated load-CMOD of plain concrete beam of size 175 mm x 50 mm x 50 mm for 50 different samples with circular aggregates

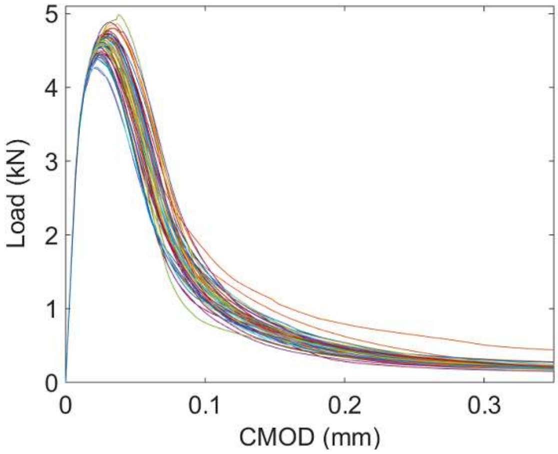

Fig. 11.Simulated load-CMOD of plain concrete beam of size 175 mm x 50 mm x 50 mm for 50 different samples with elliptical aggregates

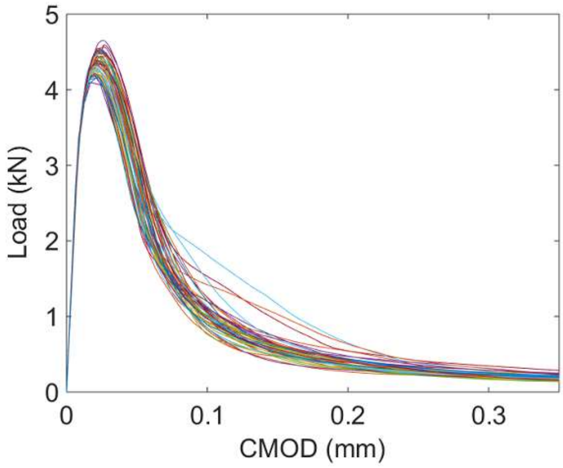

Fig. 12.Simulated load-CMOD of plain concrete beam of size 175 mm x 50 mm x 50 mm for 50 different samples with polygonal aggregates

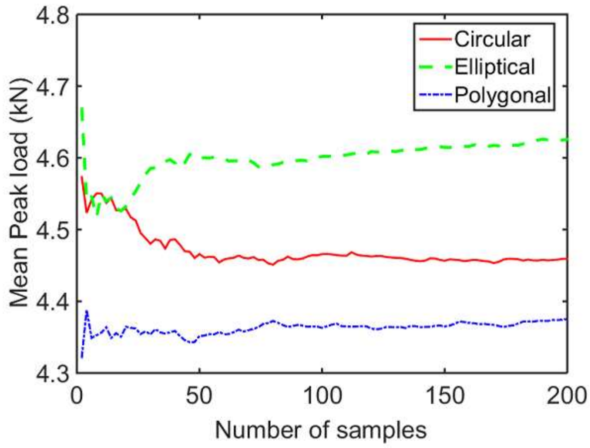

Fig. 13.Mean of peak load with number of samples in case of aggregate of three different shapes

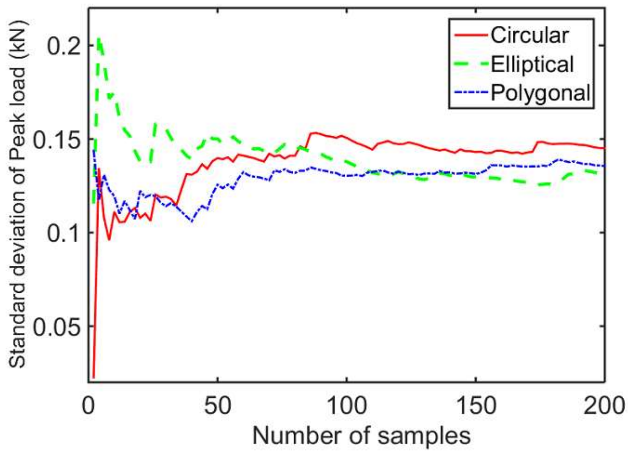

Fig. 14.Standard deviation of peak load with number of samples in case of aggregate of three different shapes

Conclusions

In this study, behavior of a concrete beam has been simulated at meso-scale considering three different shape of aggregates. The beam is subjected to three-point loading. A displacement controlled loading is used to simulate its behavior. From this study, the following scan be concluded:

- Randomness in aggregate generation and placement effect mostly the peak load and post-peak behavior irrespective of shape of aggregates. However, variation of peak load of one such sample differs less than 10 % from mean peak load.

- Mean peak load of beam specimen with polygonal shape aggregate is lesser than the circular and polygonal type of aggregates.

- Simulating around 50 numbers of random concrete samplesis approximately sufficient to get a converged mean peak load for all the three different aggregate shape: circular, elliptical and polygonal.

Disclosures

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