Simplistic Damaged Plasticity Model for Vertically Oriented Planar Wall

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ABSTRACT

Studies on the nonlinear analysis of reinforced concrete structures have already seen a substantial rise over the past few years. Many other mathematical models have been developed to study the behaviour of concrete as well as the reinforcements. Factors such as time dependence, inelasticity, interactive effects between concrete and reinforcement, also cracking were regarded. Cracking in tension as well as crushing in compression are basically two modes of failure in concrete. Material models have been proposed for monitoring concrete behaviour, as indeed the concrete damaged plasticity (CDP) model is a potential constitutive model. The method was generalized due to the complexities of CDP principle, and a simple concrete plasticity damage model has been created in this study. The model has been further categorized to simulate structural wall behaviour. All issues in the analysis related to the efficient implementation of a finite element are discussed. Through a software based on the finite element technique, a vertically oriented planar wall was investigated in respect of 3 distinct concrete grades M45, M35 and M25. The findings of the proposed model demonstrate better correlation with prior conducted experiment and assumption related to plastic hinge mechanism

Keywords

Vertically oriented planar wall, concrete damaged plasticity, nonlinear response, plastic hinge formation

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Introduction

Since 1970, FEA of structures has evolved expressively. Researchers attempted to analyze concrete behaviour, and authored several reports. Nevertheless, behaviour of concrete is complicated, also for carrying out the analysis several parameters need to be considered. Composition of concrete include various material types, qualitatively as well as quantitatively. Different properties are exhibited by these materials in terms of tension as well as in compression. Structural mechanics is really vital, besides identification of parameters, along with the nonlinear stress-strain relationship of the concrete exposed to imposed stress conditions along with strain-hardening (also softening), guides concrete behavior more difficult. Thus, the assessment of damage in concrete is challenging. Many constitutive models are often used for the said motive, and the concrete damage plasticity (CDP) model is an example of those models. This model incorporates both the plasticity flow theory and damage concepts for the analysis of concrete structures. The plasticity of concrete damage is generally accepted as an effective and functional constitutive model for replicating concrete behaviour. Grassl and Rempling (Grassl and Rempling 2008) presented a 3-D interface model. On account of damage mechanics as well as plasticity theory this model was made, but also allowed the investigators to fluctuate the ratio of total inelastic displacements as well as permanent inelastic displacements. Finite element model was suggested by Vaghei et al. (Vaghei et al. 2014) to build a 3-D version trying to address not only precast walls but also connection. Various plasticity and damage combinations that were applied to the concrete failure models were introduced by Grassel and Jirasek (Grassl and Jirásek 2006). Two combinations stress-based plasticity & strain scalar damage forms were analysed for the local uniqueness environments. A In addition, the plastic model with triaxial damage accounted for concrete failure. Yu et al. (Yu et al. 2010) incorporated an altered plastic damage model. The CDPM's theoretical structure was used as the basis for modelling, and with help of ABAQUS, the confined concrete with non-uniform containment was modelled. The Lubliner yield criterion had been used by Zhang et al. (Zhang et al. 2010) for the triaxial compression stress states.

The Lubliner criterion was redesigned, enhancing general limitations, and thus accounted for many stress states in structural engineering. In their investigation, Kratzig and Polling (Krätzig and Pölling 2004) and Gatuingt and Pijaudier Cabot (Gatuingt and Pijaudier-Cabot 2002) evolved with many kinds of plasticity combinations and also utilized isotropic damage. Taddei et al. (Taddei et al. 2011) proposed 3-D models of finite elements for unreinforced as well as reinforced wall based on the plasticity constitutive law in concrete damages. By merging isotropic damage model based on strain measurements in elastic as well as platic state with an effective stress-based plastic model, Grassl et al. (Grassl et al. 2011) used a constitutively modelled concrete structures under rate-dependent multiaxial loading. Ananiev and Ozbolt (Ananiev and Ozbolt 2007), Lubliner et al. (Lubliner et al. 1989) & Imran and Pantazopoulou (Imran and Pantazopoulou 2001) further regarded concepts in nominal stress space that comprised plasticity formulations. Carol et al. (Carol et al. 2001) explored various plasticity as well as damage combinations. Zhang and Li (Zhang and Li 2012) introduced concrete calibration techniques under uniform as well as non-uniform confinement, using 3-D simulation based on the theory by Lubliner. A synthesis of plasticity and damage mechanics had been used by Grassl et al. (Grassl et al. 2013) to develop a constitutive model used to test structural failure. The plasticity model had been used for that reason and drew upon effective stress. Based upon effective stress, the plasticity model was developed for assessing the properties in structure in failure process. Shang et al. (Shang et al. 2012) observed a rotation caused by the force of reinforced concrete girder. They decided to apply FEA software ABAQUS to CDPM for the purposed of carrying out analysis. To validate the findingis of FEA, the results from other lab tests had been used.

Larsson et al. (Larsson et al. 2012) investigated various horizontally loaded columns constructed of lime-cement, used model of damage plasticity to carry analysis of column numerically. For the deterioration of the column stiffness same model was compensated. To learn the bond behavior limited to shear Tao et al. (Tao and Chen 2015) also used a single, comprehensive FEM. Tiwari et al. (Tiwari et al. 2015) examined curved tunnels aligned underground forced to blast loading throughout the parallel direction. Incorporating theory of concrete damage plasticity, he ascertained that damage responses deformation and stress of lining in tunnel through 3-D FEA simulations. Ancestral studies suggest, CDPM is rather complex for representing the behaviour of concrete as a constitutive law. Prospective researchers cannot completely understand this, too. The procedure of the CDP theory for vertically oriented planar wall is modified in the current study as well as described in tabulated forms. The outcomes for 3 grades of concrete are formulated in a tabulated form, while concrete parameters can be widened to many other grades too. First validation of a planar shear wall was successfully carried out in ABAQUS using the CDP theory used in the current article for understanding concrete's mechanical behaviour.

Test Specimen

Analysis of structural wall (SW21) that was previously lab tested by Lefas et al. (Lefas et al. 1990) is considered in this paper with simplistic approach. SW21 was tested under static horizontal load applied on the upper beam. Wall having dimension as 650 mm x1300 mm x 65 mm with aspect ratio of 2. Horizontal load is applied to the walls, on the upper beam having length as 1150 mm, width of 150 mm and depth of 200 mm. It also acted as an enclosure for anchoring vertical bar. The wall is linked to a lower beam as well as upper beam which behaves monolithically. The lower beam is designed with fixed constraints having length, width and depth as 1150 mm, 300 mm and 200 mm respectively. The model with measurement together with the reinforcement details are shown in Figure 1. The vertical of 8 mm and horizontal reinforcement of 6.25 mm diameter consists of HYSD bars.

The edges of the wall were confined by further adding horizontal reinforcement by way of stirrups. Table 1 summarizes the characteristics of the concrete as well as of steel. At a load of 127 kN, the laboratory model SW21 deformed 20.61 mm. Figure 5. shows how the test result as well as analytical result are compared for vertically oriented planar wall using load-displacement curve, while Figure 6 show the crack pattern when SW21 fails.

Table 1 Material properties of structural wall specimen

Wall	Concrete		**Steel**	
Properties	f_c (MPa)	E_c (MPa)	**f_y (MPa)**	**E_s (MPa)**
SW21	45	33541	415	200000

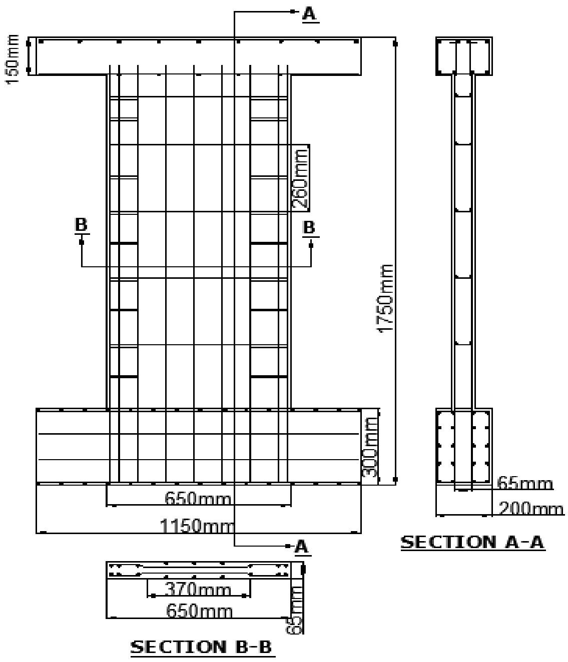

Figure 1 Dimension and reinforcement pattern of SW21 (Lefas et al. 1990)

Validation

For SW21 model a parametric investigation is considered based on different parameters that could be used to describe the formation of plastic hinges in vertically oriented planar wall. The value of the plastic strain (PE), Equivalent Plastic Strain (PEEQ), Stress (Mises), State of damage in elements (SDEG) are also explored in this analysis. The maximum displacement of 19.52 mm was perceived at the top of the SW21 under lateral load of 127 kN.

These analytical results, along with the error of around 5 percent, are in perfect agreement with the test results. Figure 2 indicates that at start of the simulation till the load of 127 kN, the displacement at the top was seen as expected, the vertically oriented planar wall's load-deflection response agrees closely with the experimental response.

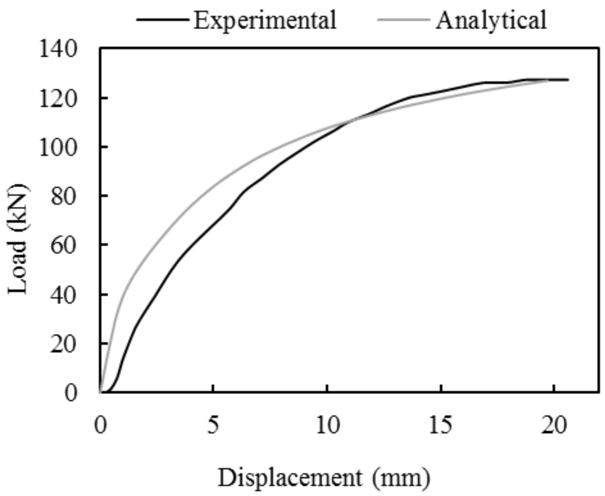

Figure 2 Comparability of load vs displacement curve

Finite Element Modelling

For performing FEA simulations, ABAQUS CAE is used. All the assumptions of modelling are summarized down with a short narration of concrete modelling.

ABAQUS Concrete damaged plasticity model

In CDPM, total strain ' ε ' consists both elastic strain ' ε_e ' is well as the plastic strain ' ε_p '.

$$\varepsilon = \varepsilon_e + \varepsilon_p \quad (3.1)$$

The relationship of stress-strain is as follows:

$$\sigma = (1-D)E_o(\varepsilon - \varepsilon_p) \quad 0 < D < 1 \quad (3.2)$$

where E_o and D, are the initial elastic stiffness and scalar degradation variable respectively.

Stress mapping indeed done under constant stress, in accordance with continuum damage mechanics by a damage tensor.

$$\bar{\sigma} = E_o(\varepsilon - \varepsilon_p) \quad (3.3)$$

The rate of change in plastic strain as in expression 3.4 developed through scalar function 'G'.

$$\dot{\varepsilon}_p = \dot{\lambda}\frac{\delta G}{\delta \bar{\sigma}} \quad (3.4)$$

where, G is the flow potential function accepted from Drucker-Prager hyperbolic function and $\dot{\lambda}$ is plastic consistency parameter (Positive function).

The hyperbolic function by Drucker-Prager expressed as:

$$G = \sqrt{\bar{q}^2 + (f_c - mf_t \tan\beta)^2} - \bar{p}\tan\beta - \sigma \quad (3.5)$$

where, f_c, Concretes uniaxial compressive strengths, f_t is concrete's tensile strengths, m is plastic potential surface's eccentricity and β is dilation angle.

CDPM utilizes the yield function suggested by Lee and Fenves (Lee and Fenves 1998) and Lubliner et al. (Lubliner et al. 1989) to take into account numerous cases of evolution in strength in compression and tension. Shown below is the yield function:

$$F = \left\{\left(\frac{1}{1-\alpha}\right)\left(\bar{q} - 3\alpha\bar{p} + \theta(\tilde{\varepsilon}^{pl}) < \bar{\sigma}_{\max} > -\gamma < -\bar{\sigma}_{\max} >\right) - \bar{\sigma}_c(\tilde{\varepsilon}_c^{pl})\right\}$$

where,

$$\alpha = \frac{\left(\frac{f_{bo}}{f_{co}}\right) - 1}{2\left(\frac{f_{bo}}{f_{co}}\right) - 1} \quad 0 \le \alpha \le 0.5 \quad (3.7)$$

$$\theta\left(\bar{\varepsilon}^{pl}\right) = \frac{\bar{\sigma}_c\left(\bar{\varepsilon}^{pl}\, c\right)}{\bar{\sigma}_t\left(\bar{\varepsilon}^{pl}\, t\right)}(1-\alpha) - (1+\alpha) \quad (3.8)$$

$$\gamma = \frac{3(1-K_c)}{2K_c - 1} \quad (3.9)$$

where, $\bar{\sigma}_{max}$ s maximum effective principal stress, $\bar{\sigma}_c\left(\bar{\varepsilon}^{pl}\, c\right)$ & $\bar{\sigma}_t\left(\bar{\varepsilon}^{pl}\, t\right)$ are effective compressive and tension cohesion stress respectively and f_{bo} & f_{co}, compressive strength under biaxial loading uniaxial loading respectively.

Various parameters are there related to defining the concrete damage plasticity model. Mathematical relationships of absolute stress-strain curves must be given in the compression damage curve as well as tension damage curve. Concrete under uniaxial stress initially exhibits a linear elastic relationship in the concrete damaged plasticity model before it hits peak tensile stress. At this point, micro cracking begins to develop in the concrete that resembles a softening stress-strain relationship in the macroscopic context. It continues to the point where the stress approaches very low values close to zero; where it can be assumed the failure of concrete. A linear elastic relation until initial yield stress ' σ_{co} ' under uniaxial compression is followed by concrete, accompanied by the plastic area where stress hardening characterizes the relationship accompanied beyond the ultimate stress ' σ_{cu} ' by strain softening.

To carry simulation of the tensile behaviour of concrete in CDPM, the feedback provided were that of tensile stress and cracking strain relationship, damage parameter and cracking strain relationship & Young's Modulus for the relevant grade and concrete's constitutive model chosen.

$$\varepsilon_t^{ck} = \varepsilon_t - \varepsilon_{el} \quad (3.11)$$

$$\varepsilon_{el} = \sigma_t / E_t \quad (3.12)$$

where, ε_t^{ck} is cracking strain, ε_{el} is undamaged concrete's elastic strain, ε_t is concrete's tensile strain and σ_t is concrete's tensile stress.

The ratio of degraded strength to the peak strength is found out as the damage parameter, d_t. For the precision of the damage curve is checked by ABAQUS CAE with plastic strain ε_t^{pl} is shown in expression (3.3). It is to be noted that the Figure 3. depicts E_t as E_o. Inaccurate damage curve always shows decreasing or negative tensile plastic strains that could cause error code before the analysis is carried out (ABAQUS CAE Manual, 2011). All these inputs were provided in tandem with the concrete constitutive model chosen to provide a tensile stress-strain relationship similar to Figure 3. which accounts for strain-softening, concrete reinforcement interaction and tension stiffening.

$$\varepsilon_t^{pl} = \left[\varepsilon_t^{ck} - \left(\frac{d_t}{(1-d_t)} \right) \left(\frac{\sigma_t}{E_t} \right) \right] \quad (3.13)$$

To carry out simulation of concrete's compressive behavior in CDPM, feedback provided were that of compressive stress and cracking strain relationship, damage parameter and cracking strain relationship & Young's Modulus for the relevant grade and concrete's constitutive model chosen.

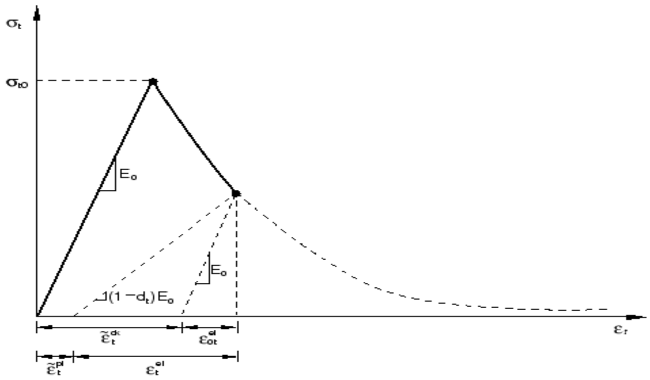

Figure 3 Parameters for tension stiffening model of concrete (ABAQUS Manual, 2016)

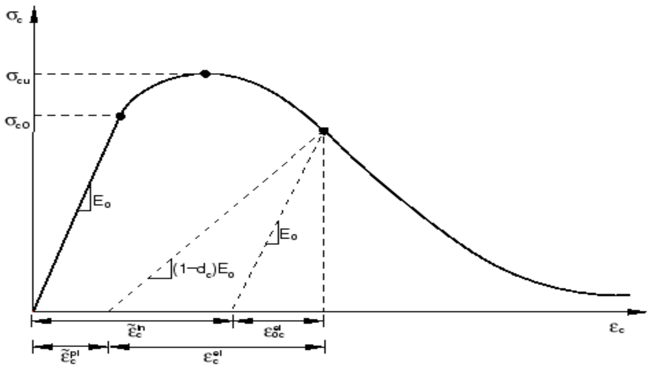

Figure 4 Parameters for compression hardening model of concrete (ABAQUS Manual, 2016)

$$\varepsilon_c^{in} = \varepsilon_c - \varepsilon_{el} \quad (3.14)$$

$$\varepsilon_{el} = \sigma_c / E_c \quad (3.15)$$

where, ε_c^{in} s inelastic strain, ε_c is concrete's compressive strain, ε_{el} is undamaged concrete's elastic strain and σ_c is concrete's compressive stress.

The ratio of degraded strength to the peak strength is found out as the damage parameter, d_c. It should be ensured that the plastic strain values ε_c^{pl} calculated using expression (3.6) are neither negative, nor decreasing with increasing stresses (ABAQUS Manual, 2011).

$$\varepsilon_c^{pl} = \varepsilon_c^{in} - \frac{d_c}{(1-d_c)} \frac{\sigma_c}{E_c} \quad (3.16)$$

In the absence of a damage parameter definition, the model acts as a plasticity model. In Figure 4., E_c is depicted as E_o. All these inputs were given in conjunction with the concrete constitutive model chosen to provide a compressive stress and strain relationship which is shown in Figure 3 which collectively accounts for compression stress hardening followed by strain softening.

Modelling methodology

Modelling of concrete is done with C3D8 (3D 8-noded hexahedral elements) and that of flexural reinforcement with T3D2 (3D 2-noded linear truss elements). The embedded constraint approach in ABAQUS helps in developing the optimal bond between reinforcement and concrete. Past research helped in considered the mesh size as 40 mm as shown in Figure 5. Static analysis is performed in ABAQUS / Standard, by subjecting model to monotonic horizontal loading. The parameters considered for CDP in this article are shown in Table 2.

Table 2 Concrete Damaged Plasticity Parameters

Dilation Angle	Eccentricity	F_{bo}/F_{co}	K	Viscosity Parameter
35	0.1	1.16	0.667	0.01

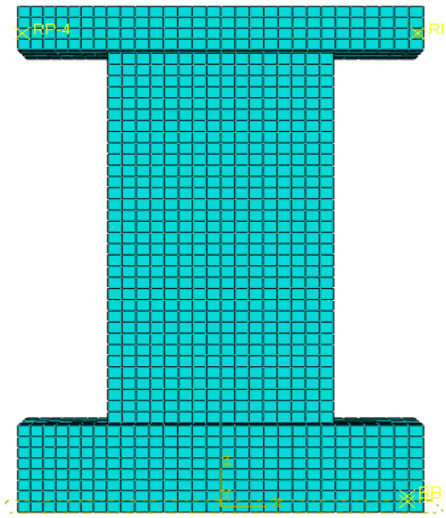

Figure 5 Mesh configuration of SW21

Finite Element Analysis

Three different concrete grades (45, 35 and 25) were implemented within the framework, respectively, as per the previously mentioned formulation of damage plasticity. Development of the scalar compression and tension damage variable for concrete grades 45, 35 and 25 has been identified accordingly. The general framework for the formulation of damage plasticity has been identified and analyzed which could be applied to every other grades of concrete between M25 and B45. Simulation done by providing a nodal displacement boundary condition centered at the top beam with a maximum displacement of 52 mm (4 percent of wall height).

Load-deflection response

Any element undergoes some deformation when a shear wall deforms. To display an overall load-displacement curve for the shear wall, the impact of the element's deformation are superimposed together. Figure 6. shows the load-displacement curve of all three grades of concrete.

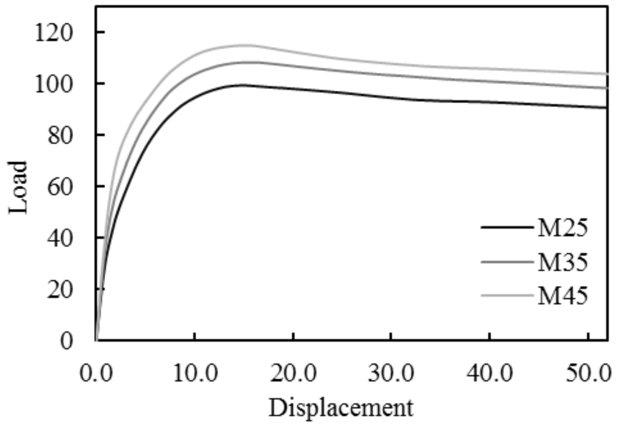

Figure 6 Load-displacement curve for different concrete grades

Cracking propagation

The cracking propagation for vertically oriented planar wall at failure is presented in Figure 7. On the tension as well as the compression side of the wall, cracking can be seen as shown. At the bottom, flexural cracks were first noticed, later the diagonal cracks were seen. After 12.5 percent of the ultimate load was applied, flexural cracks developed on the tension side near the bottom of the wall.

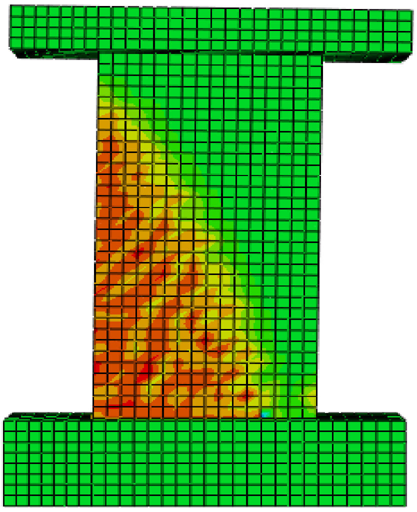

Figure 7 Propagation of cracks into the elements

The first diagonal crack appeared as the horizontal load reached 46 percent; at this point, flexural cracks already distributed a bit with slight inclination inside the wall web. New flexural as well as diagonal cracks developed due to increasing load and almost reached the compression side of the wall. Insignificant changes in crack pattern were seen beyond 86 percent of the ultimate load. For the lateral load applied, at the top one third of the wall there was no crack observed.

Plastic hinge zone

In a shear wall, development of plastic hinge in the areas with plastic behaviour rely on variety of factors. The actual physical length, the plasticity spreads over is larger and more over termed as plastic zone. It is observed that wall sections have plastic strains distributed non-uniformly, especially at the bottom one third in wall as observed in Figure 8. In nonlinear analysis methods, the shear wall's nonlinear material model is typically predicated by the plastic hinge in the structural wall on the plastic zones.

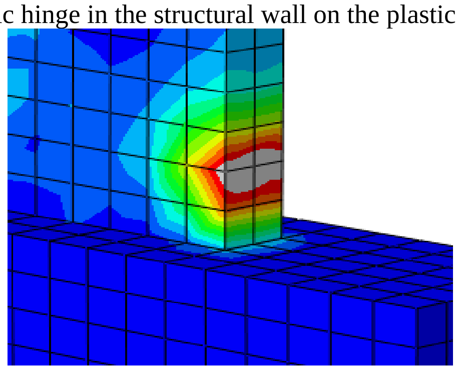

Figure 8 Plastic hinge zone on compression side at the base of wall

Conclusions

This work established the SCDP (simplistic concrete damage plasticity model). The presented model clarified the current damage plasticity model called CDP method. An amalgamation of stress-based plasticity component for a vertically oriented planar wall with a strain-based damage model it is. Results of this paper therefore identify the following assertions from the simplification of the concrete damage plasticity model:

- The SCDP model is suitable for modelling the crushing and the cracking of concrete because of its simplicity. Thus, a nonlinear 3-D model was developed with the SCDP model to test the concrete behaviour. In the developed FE model, with all possible nonlinearities, that is material as well as geometric.
- The finite element model was useful in predicting the concrete damage caused not only by concrete compressive stress and tension but also wall load-displacement response.

The plastic hinge formation at the base of vertically oriented planar wall was predicted correctly with the help of plastic strain approach. Plastic zone formed is seen in the bottom one third of wall on compression side.

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