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Ultimate load capacity of reinforced concrete shear wall for static and dynamic loads

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ABSTRACT

The present paper demonstrates the capability of ultimate load capacity evaluation with finite element code ARCOS3D for seismic shear walls used in reactor buildings. Nonlinear dynamic analyses for cyclic and equivalent static loads are carried out for shear wall specimens tested by NUPEC Japan. The experimental results are used as a benchmark test for qualifying the elasto-viscoplastic models of the code for concrete and steel reinforcement constitutive modelling. It is shown that high energy dissipation in cyclic load test can be modelled accurately near the ultimate state of reinforced concrete shear walls.

1 INTRODUCTION

In nuclear power plants shear walls are used as safety class I structures. These massive reinforced concrete (RC) wall structures serve the purpose of radiation shielding and act as a barrier against missile penetration. Due to high stiffness of these walls they resist horizontal seismic forces and restrain differential movements between adjacent floors and hence piping and equipments are least affected in case of the design basis earthquakes. In recent times evaluation of ultimate load capacity of RC structures of the reactor building and prestressed concrete (PC) class I structures such as the nuclear containment has been of interest for Indian Pressurised Heavy Water Reactors (PHWRs) [1-5]. The emphasis in this programme is to use experimentally benchmarked codes to predict the margin against various failure modes due to severe beyond the design basis accidents, resulting into containment overpressurisation, shock load on account of hydrogen detonation, aircraft impact and massive earthquake. Two in-house finite element codes ULCA [1-3] with deformation based plasticity theory using degenerate layered shell elements for static load analysis and ARCOS3D [4-5] with three dimensional brick elements using viscoplastic constitutive model for cyclic load and static analysis have been developed and validated with various experimental and analytical benchmark examples.

The present paper demonstrates the capabilities of ARCOS3D code to predict the nonlinear dynamic response of a RC shear wall tested by Nuclear Power Engineering Corporation (NUPEC), Japan. In the simulated test condition the shear wall specimens were tested by NUPEC at different target acceleration levels. The failure pattern along with responses were monitored for six test runs. The test data has been offered by NUPEC to validate nonlinear codes for modelling RC structures up to the ultimate state for dynamic and static loads. The main emphasis in this work is to simulate cyclic loading which results in significant energy dissipation. With the viscoplastic model the dynamic inelastic response could be appropriately described which are of interest for understanding the behaviour of shear wall near the ultimate state [6-7].

2 CONSTITUTIVE MODEL OF FINITE ELEMENT CODE - ARCOS3D

In the present code the most general form of viscoplastic theory [5,8-9] has been adopted which is well suited for the shear wall problem under cyclic loading conditions. It adopts 20-noded isoparametric solid finite elements with optimum 15 point integration rule which describes all the failure modes and cracks in random orientation can be modelled. The concrete and reinforcement (as smeared layer) are represented within a single element and perfect bond is assumed between steel and concrete. The strain-rate sensitive elasto-viscoplastic model for concrete consists of yield and strength limit surfaces. The yield surface defines the onset of viscoplastic behaviour and the strength limit surface defines the initiation of material degradation.The failure stress is assumed to be a linear function of the viscoplastic energy density.The rate of viscoplastic straining is modified to depend on the rate of elastic strain and on the position of the yield surface. Fracture of concrete due to crushing is a strain controlled phenomenon. Therefore, this criterion is a function of effective strain rate and second deviatoric strain increment. In this work smeared crack model is adopted with fixed crack direction which requires a cracking criterion, strain-softening rule and shear transfer across the crack. Maximum tensile strain criterion is used to predict tensile failure. At the most, two cracks are allowed to occur at each sampling point. The second crack is assumed to initiate orthogonal to the first crack.. Closing and reopening of cracks is allowed in the model following the secant path. To make the constitutive model objective with regard to the size of the finite elements used in the mesh, the softening curve is related to the fracture energy of the concrete with definition of a characteristic length as the ratio of the control volume and crack surface. Shear transfer after cracking of concrete is modelled using simplified approach which depends on the tensile strain normal to the crack plane and reduced shear modulus.

3 SHEAR WALL TEST SPECIMEN DESCRIPTION

The geometry of the flanged shear wall specimen is shown in fig.1. The web wall is 75 mm thick, 3000 mm long from flange wall centre to centre and 2020 mm clear height with a shear span ratio of 0.8. The flange walls are 100 mm thick and 2980 mm long. The percentage of reinforcement in each layer of the web wall is 1.2 %. The total additional weight to achieve target accelerations was 92.9 tonf which was lumped at the top and bottom of the top slab. The total weight of the top slab including the additional weight is 122 tonf. The rebars have yield strength of 383.6 MPa, tensile strength of 481.7 MPa , modulus of elasticity of 184.4 MPa. The concrete in the shear wall specimen has compressive strength of 28.6 MPa, modulus of elasticity of 2.296E04 MPa , splitting tensile strength of 2.24 MPa and Poisson's ratio of 0.155. The mean compressive strength of concrete for the top slab is 28.3 MPa. The total duration of the input wave was 12 seconds. In the test, the specimens were subjected to excitations only along the horizontal X-direction, i.e. the direction along the web wall. The vibration test steps were set corresponding to a series of five target response levels which were sequentially performed as RUN-1 to RUN-5 for the two specimens U1 and U2. Specimen U1 was subjected to an additional test RUN-2D which was followed by RUN-2 due to low target acceleration level achieved in RUN-2.

4 FINITE ELEMENT MODEL OF SHEAR WALL

The shear wall under base excitation is analysed in this work with isoparametric 20 noded solid brick elements .The finite element model consists of 80 solid elements in the specimen and 60 elements in the top slab. Due to symmetry, one half of the shear wall is modelled as shown in fig 2. The reinforcement details of NUPEC report [6-7] were smeared at the appropriate locations in each solid element.

5 ANALYSIS RESULTS

5.1 Nonlinear Dynamic Analysis

The fundamental frequency from the free vibration analysis of the finite element model is found to be 13.92 Hz whereas the experimental frequency is 13.2 Hz. This difference in frequency is due to the effect of inplane compressive stresses which were not considered in the free vibration analysis. The nonlinear seismic analysis has been performed using the acceleration time history data offered by NUPEC [6-7]. In the present work, horizontal excitation is applied to the model on the base of the shear wall. NUPEC has offered the test results of top slab horizontal displacements and accelerations and rebar strains for RUN-1 to RUN-5 for comparison.In this work, nonlinear dynamic analyses have been performed from RUN-1 to RUN-5 independently without considering the stiffness degradation effects in the previous runs. This mode of independent analysis has been planned mainly to avoid reruns if the computer job is terminated.The time step used was 0.002 seconds with number of steps of 6000 in each run. Viscous damping was used with a uniform damping of 1.1 % for RUN-1 to RUN-5.

The maximum input acceleration applied in RUN-1 is 530 mm/s^2. For this case the maximum displacement from the analysis is 0.25 mm whereas the experimental value is 0.29 mm. The maximum acceleration found from the analysis is 1623 mm/s^2 whereas the experimental value is 2080 mm/s^2. After RUN-1, surface cracks due to discontinuity stresses appear at the bottom of flange walls near flange-wall junction.The present code response and crack pattern are consistent with the experimental observation.

For RUN-2 the maximum input acceleration is 1120 mm/s^2. The maximum horizontal displacement at the top slab from the analysis is 0.735 mm whereas the experimental value is 0.58 mm. The maximum acceleration from the analysis is 4408 mm/s^2 whereas the experimental value is 3980 mm/s^2. The viscous damping used in RUN-2 is same as that for RUN-1 (1.1 %).

Neglect of surface cracks at the base wall junction developed in RUN-1 and use of lower damping due to independent mode of analysis for RUN-2 leads to higher displacement response prediction.

The maximum input acceleration in RUN-2D excitation was 3040 mm/s^2. The maximum horizontal displacement found from the analysis is 1.392 mm whereas the experimental value is 1.04 mm.The maximum acceleration at the top slab from the analysis is 6070 mm/s^2 and the experimental value is 6677mm/s^2. The crack pattern after RUN-2D is shown in fig.3. All the sampling points in the elements of web wall show shear cracks uniformly as it is expected. Some more locations on the flange walls have also cracked compared to RUN-1. The difference in analytical and experimental results is again due to neglect of stiffness degradation, crack history and plastic strains in the previous runs along with use of lower viscous damping in the analysis as noted earlier for RUN-2.

In RUN-3 the maximum input acceleration is 3520mm/s^2. The maximum displacement from the analysis is 1.70 mm whereas the experimental value is 1.63 mm. The analytical maximum horizontal acceleration at the top slab is 6971 mm/s^2 whereas the experimental value is 7040 mm/s^2. In this case the analytical and experimental comparison is very close due to severe cracking occurring in this test and hence previous crack and plastic strain history do not significantly affect the inelastic behaviour of the shear wall.

For RUN-4 the input acceleration is 5770 mm/s^2 and due to severe cracking the number of iterations for convergence show a marked increase which results in huge computational time for each time step. The analysis was terminated at a time of about 3.7 seconds, however the peak input acceleration to which the shear wall is subjected is taken into account. The maximum horizontal displacement from the analysis is 4 mm, whereas the experimental value is 3.7 mm. The maximum horizontal acceleration at the top slab from the analysis is 10270 mm/s^2 and the experimental value is 8820 mm/s^2.

The maximum input acceleration in RUN-5 is 12300 mm/s^2. The maximum horizontal displacement from the analysis is 7.04 mm and the experimental value is 11.1 mm. The maximum horizontal acceleration at the top slab from the analysis is found to be 14440 mm/s^2 and the experimental value is 13410 mm/s^2. This computer run was terminated at about 3.2 seconds which includes the peak input acceleration as evident from the comparison of top slab acceleration response. In the experimental test beyond this period the displacement was controlled. This resulted in a higher displacement of 11.1 mm due to stress softening in post-cracking region..

Displacement and acceleration histories for RUN-5 are shown in figs 4-5. Table 1 shows the input base acceleration data for the two specimens U1 and U2 from RUN-1 through RUN-5. Due to the low target acceleration achieved for U1 specimen in RUN-2 an additional RUN 2-D was performed by NUPEC [6-7] for only U1 specimen. It is noted that the input acceleration level in RUN-2D is 3040 mm/s^2 which is close to the input acceleration for RUN-3; hence nonlinear response is expected for RUN-2D. Table 1 also shows the top slab displacement and acceleration response reported by NUPEC. The present analysis was carried out for specimen U1 for all the six acceleration levels. The analytical displacement and acceleration values are also presented in this table.The percent difference in displacement (acceleration) in comparison to the experimental values for U1 specimen are -13.8% (-22%) for RUN-1, 27.6% (10.8%) for RUN-2, 33.7% (10%) for RUN-2D, 4.29% (-0.98%) for RUN-3, 7.82% (16.4%) for RUN-4 and -36.6% (7.68%) for RUN-5.

In RUN-1 the surface cracks appear at the base wall junction; so actual damping is close to 1.1% and hence dynamic behaviour is closely predicted in the analysis. Neglect of these surface cracks in RUN-2 results in overprediction of response (~27.6%) which is even higher in RUN-2D (~33.7%). In RUN-3 and RUN-4 severe cracking takes place and hence nonlinear responses are not strongly influenced by previous crack history and inelastic strain history. This is even evident from the difference in experimental response in RUN-3 for U1 and U2 specimens (this comparison is valid as RUN-2D and RUN-3 input acceleration levels are of same order). Since U2 specimen is subjected to higher input acceleration levels compared to specimen U1 in RUN-1 and RUN-2, the experimental response is accordingly higher for U2 specimen for these two cases. RUN-2D is only performed for U1 specimen; hence in RUN-3 the experimental displacement for U2 specimen is higher than for specimen U1 (2.68 mm for U2 compared to 1.63 mm for U1). Due to absence of RUN-2D for U2 specimen; inelastic strains and cracks are not developed to a significant level and hence larger experimental displacement is observed although the input acceleration levels for RUN-3 are of same order (3520 mm/s^2 for U1 and 3480 mm/s^2 for U2). It is noted that for RUN-5 the acceleration amplification is 1.00 compared to 1.17 observed in the analysis. Thus an equivalent static analysis can be performed with due consideration to accumulated plastic strain and cracking. This is presented in the next section 5.2.

5.2 Nonlinear Static Analysis

In the present work, a nonlinear static analysis has been performed under monotonic horizontal loading at the top slab level.The main aim of this analysis is to find out the ultimate capacity of the shear wall for equivalent inertial horizontal load at the top slab level. This equivalent static analysis overcomes the limitations of dynamic analysis as it accounts for the stiffness degradation due to cracking, crack history and inelastic strains from previous loads corresponding to the maximum inertia loads of the individual test runs. The model used for this analysis is same as that of the nonlinear dynamic analysis. The load-displacement behaviour is shown in fig 6. From the figure very good agreement between results of experiment and finite element code ARCOS3D is noted for all the test runs.

6 CONCLUSIONS

The NUPEC tested RC shear wall is analysed using the finite element code ARCOS3D. Free vibration, nonlinear dynamic and nonlinear static analyses have been performed. In the case of dynamic analysis the differences between experimental and ARCOS3D code results for RUN-2 and RUN-2D are due to assumed constant damping of 1.1%, neglect of stiffness degradation and crack history in the previous runs. This behaviour is consistent with the differences noticed even between the two experimental results for U1 and U2 specimens. This is resolved by carrying out equivalent static analysis which accounts for inelastic strain history. In dynamic analyses for

RUN-3 and RUN-4 very good comparison between the present analytical and experimental results near the ultimate state (where most of the cracking takes place) is noted. For RUN-5 in post failure softening region dynamic and static analyses show lower bound values; further improvement in equation solution scheme is desirable. It may be concluded that viscous damping is only important for surface cracks. Energy loss on account of cracking near the ultimate state can be analysed by the viscoplastic model of concrete in case of cyclic loads.

7 REFERENCES

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Table 1 Comparison of Analytical (ARCOS3D CODE) and NUPEC Test Results

Max Input accln.(mm/s^2)			**Maximum top slab accln.(mm/s^2)**			**Maximum top slab displ (mm)**		
RUN	**U1**	**U2**	**U1**	**U2**	**ARCOS3D**	**U1**	**U2**	**ARCOS3D**
RUN-1	530	710	2080	2420	1623	0.29	0.35	0.25
RUN-2	1120	2290	3980	5000	4408	0.58	0.89	0.74
RUN-2D	3040	--	6070	--	6677	1.04	---	1.39
RUN-3	3520	3480	7040	8290	6971	1.63	2.68	1.70
RUN-4	5770	4380	8820	8620	10270	3.71	3.91	4.00
RUN-5	12300	9600	13410	13300	14440	11.1	11.5	7.04

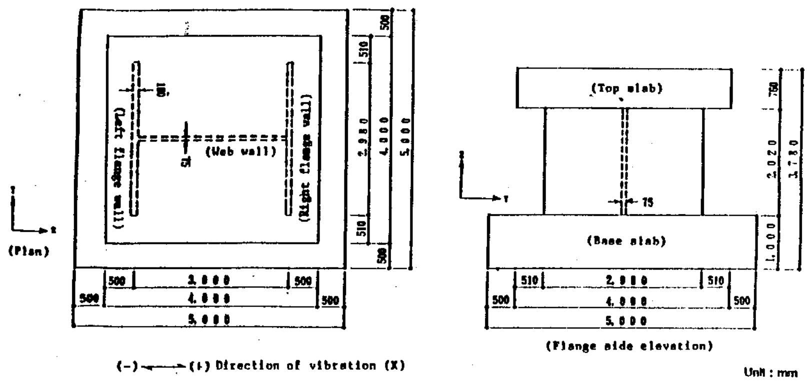

FIG. 1 SHEAR WALL TEST SPECIMEN

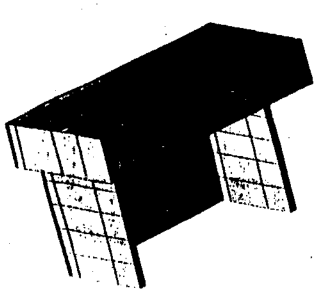

FIG. 2 3D MODEL OF RC SHEAR WALL

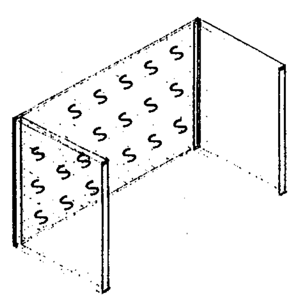

FIG. 3 CRACK PATTERN IN RUN 2D

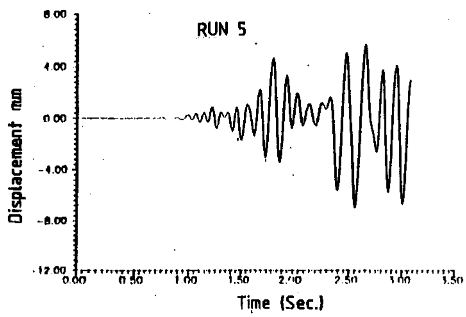

FIG. 4 HORIZ. DISPLACEMENT

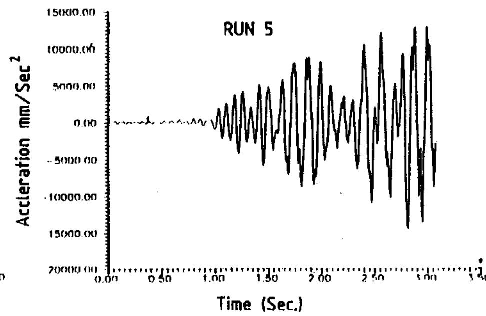

FIG. 5 HORIZ. ACCELERATION

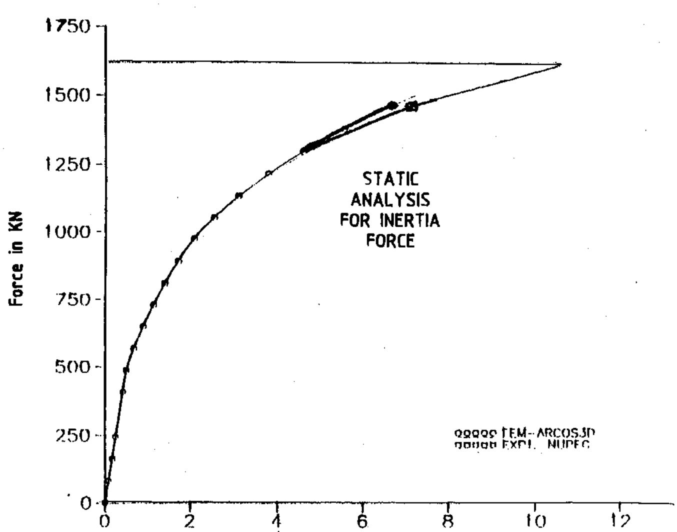

FIG. 6 LOAD-DISPLACEMENT BEHAVIOUR OF RC SHEAR WALL UNDER HORIZONTAL FORCE