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BEHAVIOUR OF REINFORCED CONCRETE KNEE BEAM-COLUMN JOINT IN CASE OF GROUND CORNER COLUMN LOSS-NUMERICAL ANALYSIS

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Abstract. *Prevention of a progressive collapse event of a reinforced concrete structure is a key design consideration. Commonly a sudden column loss scenario is analyzed to ensure the structure has suitable robustness; however, there is still a lack of numerical information regarding the influence of the dynamic effects involved. Beam-column joints are a critical part in reinforced concrete frames designed for inelastic response to severe external loads. Structural response for an inverted knee beam-column joint which results from the loss of a ground corner column are performed in this study using LS-DYNA. The sudden failure of the ground corner column may turn the exterior beam-column joint into an inverted knee beam-column joint with some reinforcement requirements deficiencies. Three-dimensional finite element (FE) models of a knee beam-column joint are described and verified with experimental results available in literature; this is followed by a parametric study to investigate the influence of different types of anchorage for beam longitudinal bars. In addition to that, the effect of using additional joint vertical stirrups is examined numerically. It is shown that the various types of reinforcement anchorage in beams have significant effects on shear capacity, load-deflection characteristics and failure modes of knee beam-column joints. Anchorage beam bars with U shape produces better inelastic behaviour than 90° standard hooks and headed bars. Contribution of additional joint vertical stirrups is more influential with headed bars anchorage than with the other two anchorage types.*

1 INTRODUCTION

Reinforced concrete is the principal material used for structures engineering. From a safety point of view it is important that a concrete structure especially its connections, should have an adequate amount of continuity, integrity and high load carrying capacity, in order to exhibit ductile behavior that allows redistribution of forces after events, such as the loss of a ground column. Local failure shouldnԏt lead to total collapse of the structure.

The response of a structure after an initial damaging event is a critical consideration. This is reflected in the Eurocodes basic requirements that:

óA structure shall be designed and executed in such a way that it will not be damaged by events such as explosion, impact, and the consequences of human errors, to an extent disproportionate to the original cause.ô[1] This has led to the use of the sudden column loss scenario in which a key vertical element is removed and the structure analyzed to predict if further failure is likely. This situation has been investigated by a number of authors to determine the failure mechanisms and ultimate capacity of a damaged structure both steel [2] and Reinforced Concrete (RC) [3-6]. Progressive collapse experimental simulation after a sudden damaging event is time consuming, expensive and requires experience in order to achieve accurate results. Alternatively, the finite element method is a powerful tool for structural analysis. The majority of numerical investigations of the behavior of reinforced concrete members under a column removal scenario involve two-dimensional idealizations. This simplification provides good results with Dirk et al. [7] for a slab membrane tensile action investigated numerically with DIANA, but in case of beam-column joints, the results may be of questionable accuracy; how to consider joint stirrups confinement effect. Three- dimensional modeling has many advantages over the two-dimensional idealizations, in terms of applying load and specifying boundary conditions close to the real structure; also dilation of concrete and confinement effects may be taken into account. Yi et al, [3] conducted in-depth studies on the reinforced concrete assemblies under a column removal scenario using LS-DYNA simulating the improvement of its behavior by catenary action mechanism.

Corner ground column disappearing turns an exterior beam-column joint into an inverted knee joint; this may lead to some reinforcement deficiencies, such as the absence of joint vertical stirrups and column longitudinal bars with poor anchorage conditions. LS-DYNA program proposes several advanced constitutive models to simulate concrete material; most of them have the option of automatic generation of parameters to help users during the input phase. However, these sets of automatically generated parameters are based on reference experimental data that could not match very precisely with concrete properties in some cases. Therefore, one has to be careful about this point and must investigate these models with sensitivity analysis and optimizations to be sure that the modeled behavior is as close as possible to the real one. The general approach for reinforced concrete modeling; which is proposed in this paper, contains several important steps. The first one includes boundary conditions, hourglass treatment, mesh size, proper coupling algorithm for connecting both concrete solid element and reinforcement beam elements, also for reducing required CPU time, selective mass scaling technique will be implemented to achieve larger explicit time step. The second step is to get results for real case using different concrete material models with automatic parameters generation, followed by fitting and optimization of material parameters to match as possible the available experimental results in literature. The third step is a parametric study to investigate the influence of different beam bar anchorage types and the effect of joint vertical stirrups absence.

2 DESCRIPTION OF THE REFERENCE SELECTED EXPERIMENTAL TESTS

A series of well monitored experiments on RC beam-column knee joints were performed at Clarkson University by Wallace et al. [8] and at Chongqing Jiaotong University by Peng et al. [9]. The present paper offers the numerical simulation of these tests using LS_DYNA. The purpose of this study is to evaluate the efficiency of the numerical model and the used material models to predict the structural response for further parametric analysis.

2.1 Wallace specimen

The knee beam-column joint studied by Wallace et al., consists of a beam portion and column portion. The column has a cross section of 400 mm x 400 mm with an overall length of 1100 mm and the beam has a cross section of 280 mm x 400 mm and the length of the clear portion is 1100 mm. The beam-column joints are designed assuming that points of contra-flexure occur at the mid-height of columns and at the mid-span of beams. The top and bottom longitudinal reinforcements in the beam are bent down and up into the column. The beam is reinforced using 5ȅ18 mm as top and 3ȅ18 mm bottom longitudinal bars and ȅ10 mm as transverse steel repeated each 90mm. The column is reinforced with 8ȅ20 mm as longitudinal bars and ȅ10 mm ties spaced 90 mm. The dimensions and reinforcement details of the specimen is shown in Figure 1. Detailed design details of the specimen can be found in [8].

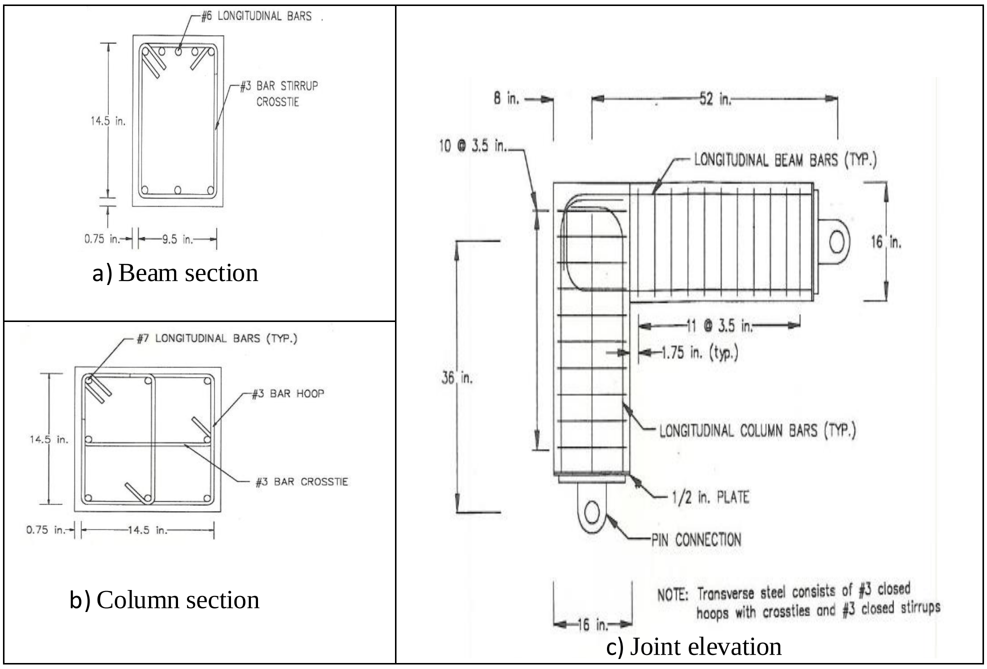
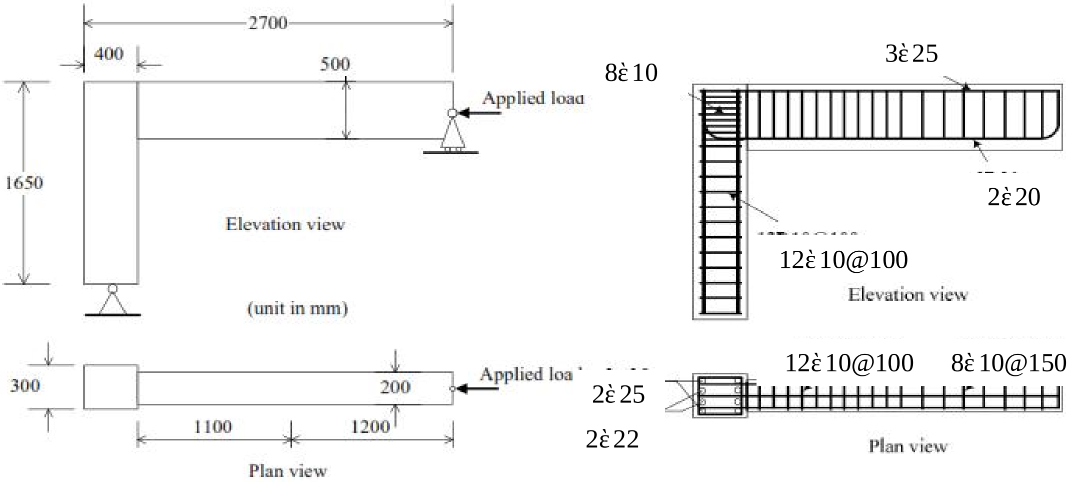


Figure 1 : Dimension and details of knee joint [8] (all dimension in inch).

2.2 Peng specimen

Peng and Wang [9] evaluated a series of non seismically detailed knee beam-column joints subjected to monotonic horizontal loading. The specimen represents an ñas-builtò corner beam-column joint subassemblage consisting of a column and beam; the lengths of the column and beams are chosen to correspond to the contra þexural points under lateral load, assumed to occur at the mid-height and mid-span of the frame. The dimensions and reinforcing details of the specimen is shown in Figure 2. The joint core contains no vertical transverse reinforcement. Beam longitudinal bars are anchored in the joint with 90° standard hooks. The column has a

300x 400 mm cross section, and the beam is 200 mm wide x 500 mm deep. The beam is reinforced using 3ὲ25mm as top and 2ὲ20mm bottom longitudinal bars and ὲ10 mm as transverse steel repeated each 100mm. The column is reinforced with 4ὲ22 and 4ὲ25 mm as longitudinal bars and ὲ10 mm ties spaced 100 mm. More details about the specimen can be found in [9].



a) Dimension and boundary condition b) Steel reinforcement details

Figure 2 : Dimension and steel reinforcement details of knee joint [9] (all dimension in mm).

3 FINITE ELEMENT MODEL DEVELOPMENT

The first step, the description of the model includes structural geometry and element type, modeling of materials, boundary conditions and simulation time.

3.1 Structural geometry and element type

Figure 3 shows the three-dimensional FE model of the RC beam-column knee joint tested by Wallace et al., with two different mesh sizes. In order to improve the accuracy of the results while reducing computational cost, a mesh sensitivity analysis was carried out. Eight node solid elements with a single integration point were used to represent concrete; one disadvantage with one-point integration is the need to control the zero energy modes that arise, called hourglassing modes. In order to control these modes, LS-DYNA has several hourglass control types. Beam elements (2-node Hughes-Liu beam element) were used to model steel reinforcing bars.

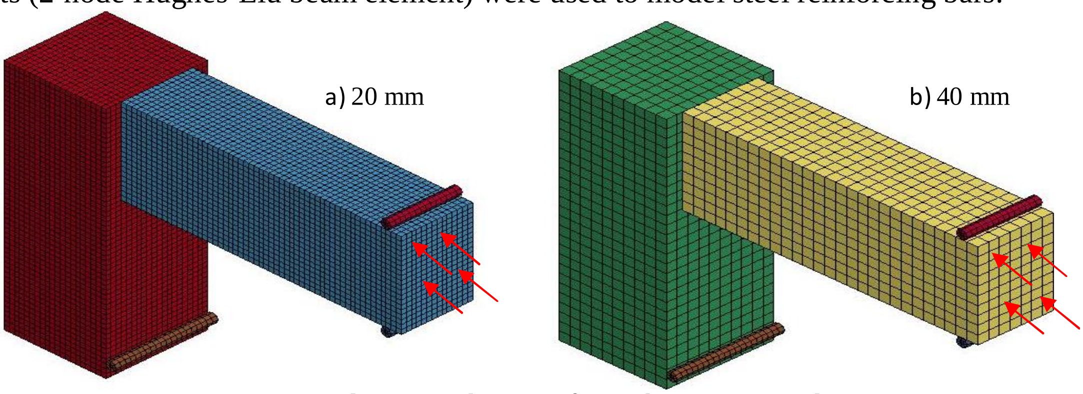


Figure 3 : Finite element meshes sizes for mesh sensitivity analysis.

3.2 Modeling of materials

Concrete

A good concrete model must consider the elasticity of concrete prior to cracking and the subsequent plastic states on the onset of cracking and beyond [10].

LS-DYNA has several material models to model concrete behaviour such as:

- Plasticity based Karagozian and Case concrete damage model designated as MAT_72_R3 in LS-DYNA [11];
- Continuous Surface Cap Model designated as MAT_CSCM_159, which is a visco-elastic-plastic concrete model [10].

These two materials models were used in this study to check which one is most suitable for this case study and able to give close results to the experimental ones. Table 1 presents properties of the used concrete material models.

Material ID in LS_DYNA	Material title in LS_DYNA	Supported element types	Strain rate sensitivity	Failure criteria	Equation of state requirement
72	Concrete damage	Solid	Yes	Yes	Yes
159	CSCM	Solid, shell	Yes	Yes	No

Table 1: Concrete material models in LS-DYNA [12].

Steel reinforcement

The steel reinforcement bars (longitudinal and shear reinforcements) were modeled as a strain sensitive uniaxial elastic-plastic material. The material model PIECEWISE_LINEAR_ PLASTICITY (MAT_024) from LS-DYNA was used in this study.

The concrete and steel elements require a good coupling mechanism in order to achieve interaction between the two parts; this analysis uses the CONSTRAINED_ LAGRANGE_ IN_SOLID formulation to achieve a proper interaction.

3.3 Boundary Conditions

Modeling of boundary conditions is often the most critical aspect in achieving sensible, reliable data from a finite element model [13]. The load on the beam-column joint is applied by specifying a prescribed horizontal displacement to the nodes of the beam end as shown in Figure 3. To simulate simply supported conditions, a selection of beam end nodes were prevented from vertical movement and a selection of column end nodes were prevented from both vertical and horizontal movement as shown in Figure 3.

3.4 Event Simulation Time

The flexural frequency of vibration was computed analytically for the two beam-column joints using conventional formulas of vibration theory [14]. Table 2 shows the computed flexural frequency of vibration for the two beam-column joints and the corresponding period of vibration. The event simulation time was chosen to be 1.5 sec which is approximately more than 100 times the period of flexural vibration for the Wallace specimen. Consequently, inertial effects are assumed to be negligible and the model can be used to represent a quasi-static experiment.

Knee joint ID	Flexural frequency of vibration	Flexural period of vibration
Wallace	543.19 rad/sec	0.01157 sec
Peng	276.104 rad/sec	0.0227 sec

Table 2: Analytical flexural period of vibration for reinforced concrete beam-column joints.

3.5 Run Time

A shortcoming in using an explicit code to simulate a quasi-static experiment is the fact that it can result in excessive run times which may limit mesh refinement trials. In order to control run time, a selective mass scaling card is implemented in this study, to increase the critical time-step for explicit time integration without adulterate the global solution; it is applied to limited regions with very small critical time steps [15]. For the finite element simulations presented in this study, the cost in CPU run time varied approximately from half hour to 11 hours (depending on the dimension of model and element size) for 1.5 sec. of event simulation time, on a Pentium III PC 600 MHz dual processor with 512 MB of RAM with LS-PrePost processor software version 4.1 with Finite element software LS_DYNA solver version ls-dyna_smp_d_R700_winx64 _ifort 101.exe. It should be recognized that for quasi-static structural problems, implicit methods are usually more effective than explicit methods; however, this depends on severity of non-linearities, which are present in the current study. It is very difficult to model the non-linearities and progressive damage/failure using an implicit code.

4 COMPARISON OF EXPERIMENTAL AND NUMERICAL RESULTS

A number of models were created with varying mesh sizes using different concrete material models for knee beam-column joints. In this paper, the results are presented for four simulations of the knee joint tested by Wallace et al, using Concrete Damage and CSCM concrete models, followed by simulation using selective mass scaling to determine how it affects the solution speed and added mass percentage as well.

4.1 Load vs. horizontal deflection of the knee joint

In order to simulate the experimental conditions, the models were analyzed in displacement control in LS-DYNA. Figures 4-6 show the numerical results in comparison with the experimental curve of the load vs. the horizontal joint displacement. Table 3 shows the maximum lateral load carrying capacity for the different mesh sizes with different concrete material models and the approximate run times associated with each of the mesh sizes. Table 3 also shows the number of elements associated with each mesh size and the corresponding disk space requirements.

From Figures 4-5, lateral load carrying capacity increases with decreasing mesh size, converging to the experimental at a mesh size of 20 mm. Figure 4 shows that the primary stiffness of the model was over estimated in the numerical analysis. The simulation was able to reproduce the main features of the joint behaviour such as the joint ultimate capacity, the resulting cracking pattern and the displacement capacity. Figure 6 shows agreement between the numerical results for the Peng specimen with available experimental and Abaqus results by Peng.

4.2 Crack profiles for different simulations

The damage in the RC model is shown by plotting the fringes of effective plastic strain. These effective plastic strain contours reveal the strain localization where failure propagates. The first experimental flexural crack appeared at the beam-column interface at the displacement of 2.2 mm which is relatively close to the first numerical crack which appeared at 3 mm displacement; the cracks in the beam and column were attributed to bending at low displacement level, but appeared to be a result of combination of shear and bending in advanced loading stages. At higher loading level, cracks continued to form, usually where stirrups or hoops were located. Figure 7 shows the cracking pattern of the RC knee joint in the numerical simulation. From these comparisons, it can be observed that the damage plot in the numerical simulation can capture the typical crack profiles of the RC knee joint under closing moment. Closer examination of results for the two mesh sizes with different concrete material models show a small variation in the damage profile. The finer mesh size of 20mm with the CSCM model seems to show, a more accurate pattern of cracks damage profile as compared to other trials.

Mat ID , mesh size		No. of elements	Load carrying capacity [kN]	Approximate Run Time[sec]	Disk space used [B]
Wallace	CSCM, 20 mm	39208	274	20580	10259865
	CSCM, 40 mm	5504	194	1920	2863466
	KC3, 20 mm	39208	116	18341	9816368
	KC3, 40 mm	5504	105	1385	2788226
	CSCM, 20 mm, SMS	39208	291	8634	2883213
	Experimental= 264 kN			Analytical= 275.3 kN	
Peng	CSCM, 25 mm	64500	200	38650	10352654
	Experimental= 200 kN			Analytical= 192.7 kN	

Table 3: Mesh and concrete material models sensitivity analysis.

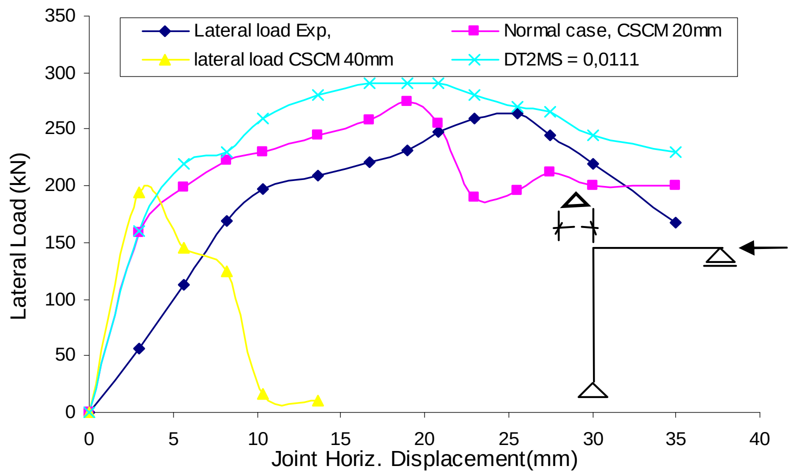


Figure 4 : Lateral Load versus Joint Displacement for Wallace specimen and different simulations.

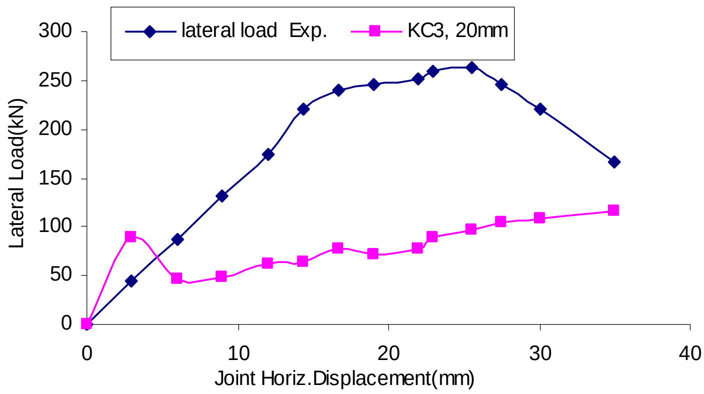


Figure 5 : Lateral Load versus Joint Displacement for Wallace specimen and concrete damage model KC3.

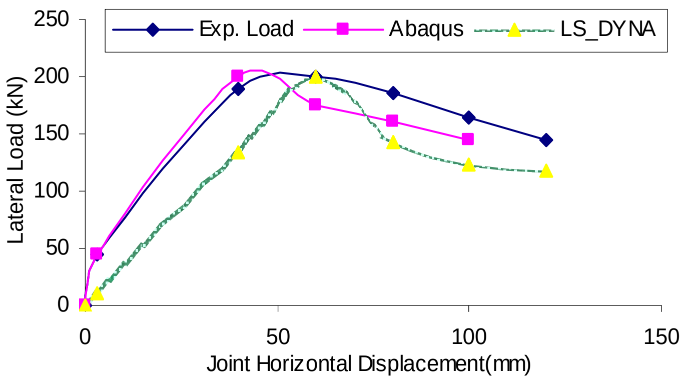
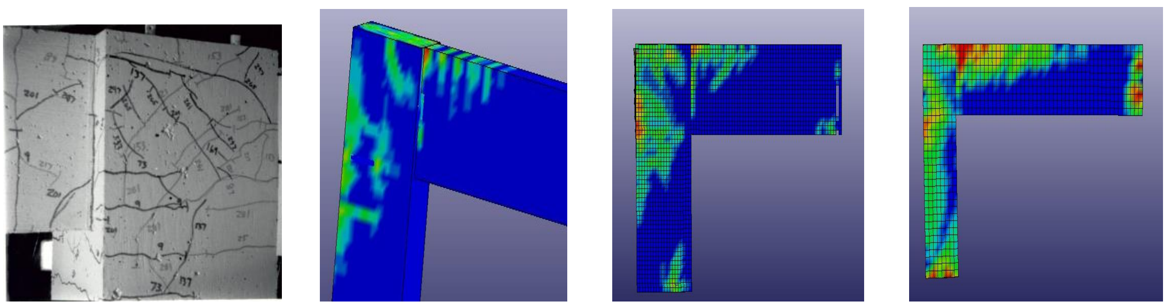


Figure 6 : Lateral Load versus Joint Displacement for Peng specimen and different simulation tools .



a) Typical crack pattern   b) First flexural crack   c) Final cracks, CSCM, 20   d) Final cracks, CSCM, 40

Figure 7 : Comparison of cracking pattern of RC joint with different element sizes for mesh sensitivity analysis.

In one of simulations, selective mass scaling (SMS) was used in order to increase the critical time step to reduce the overall computation time; the change in mass is tracked and observed in order to check if it is acceptable. Figure 8 shows that this simulation with SMS has a trivial increase for model kinetic energy (less than 1% internal energy); SMS significantly decreases computation time with trivial effect on results. In the further sections, the ýnite element models are used to investigate the inþuence of various parameters on the load carrying capacity of knee beam-column joints.

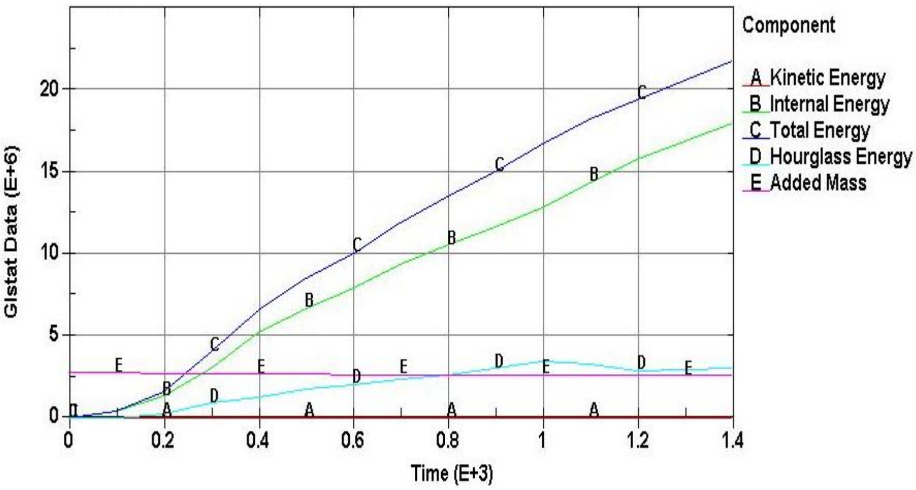


Figure 8 : Model energy balance with selective mass scaling.

5 PARAMETRIC STUDY

After verification of the FE model with respect to the experimental results, this section presents a parametric investigation to find more information about the behavior of RC knee joints with different reinforcement details. The response of the RC knee joints was studied by varying some key parameters such as joint vertical stirrups absence and using column longitudinal bars with poor anchorage condition simulating the case after ground column loss. Next, beam longitudinal bars may be anchored by 90° standard hook, headed end and U shape end. Figure 9 presents schematic drawings for the beamôs different anchorage ends.

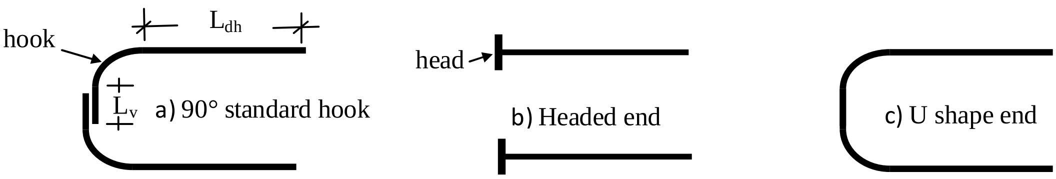


Figure 9 : Different alternatives for beam bars end anchorage.

The anchorage conýgurations in Fig. 9-a encompasses the following details: (1) horizontal anchorage (L_{dh}), (2) hook and (3) extension of the hook (L_v). The minimum horizontal anchorage (L_{dh}) is necessary to transfer the tensile stress in the þexural reinforcement in to the joint. The hook is responsible for the formation of the compression strut which in the case of knee joints is one of the major load transfer mechanisms from beam to column through the joint core. Sufficient extension (L_v) tail of the hook is necessary to prevent the pullout of þexural reinforcement. Figure 9-b presents headed bar ends by mounting a steel plate at the bar end instead of the hook portion and itôs vertical tail, in order to decrease steel congestion and ease concrete placement. Figure 9-c presents a U shaped bar by adjoining both top and bottom reinforcement in one in order to improve bond resistance between concrete and the beam main rebar.

The monotonic load displacement behaviour of these anchorage conýgurations with and without joint vertical stirrups are compared in Figures 10 to 13. Slippage of column longitudinal bars and joint shear failure observed in all the modeled joints is a direct consequence of the absence of good anchorage condition for column longitudinal bars. Among the considered anchorage conýgurations, the headed end without joint vertical stirrups exhibited the weakest behavior when compared to other conýgurations; this explained by the fast rotation of the beam top bars at the beam-column interface, which goes together with accelerated bond deterioration. This may be observed in figure 13, in the elastic part of the curve. Figure 11 shows that a U shaped bar is observed to have better performance when compared to the other anchorage conýgurations. This can be attributed to the better conýnement of the joint core concrete. It can also be observed from figure 12, that the strength enhancement is more evident in the case of headed bars with additional joint vertical stirrups when compared to the other anchorage cases; this can be attributed to the better conýnement of joint core concrete and the avoiding of rotation of the beam top bars.

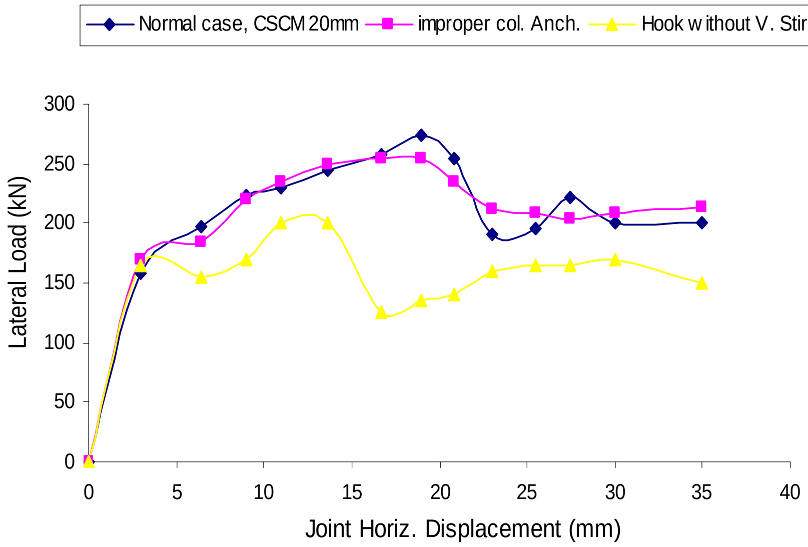


Figure 10 : Stirrups effect on RC joint with improper column bars anchorage and hooked beam bars anchorage.

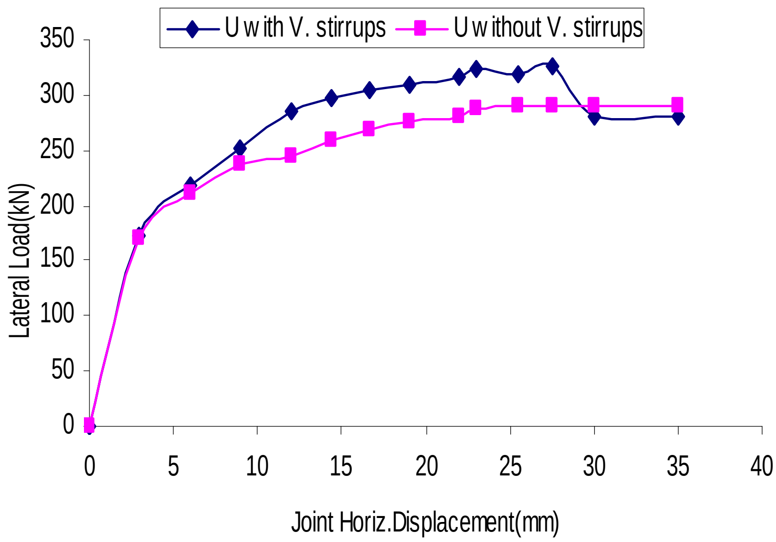


Figure 11 : Stirrups effect on RC joint with improper column bars anchorage and U shaped beam bars.

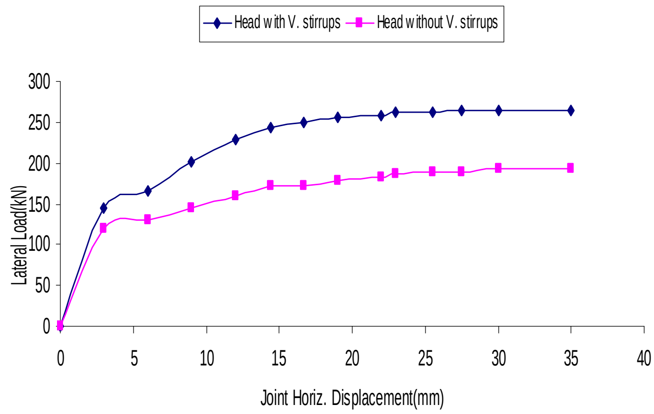


Figure 12 : Stirrups effect on RC joint with improper column bars anchorage and headed beam bars anchorage.

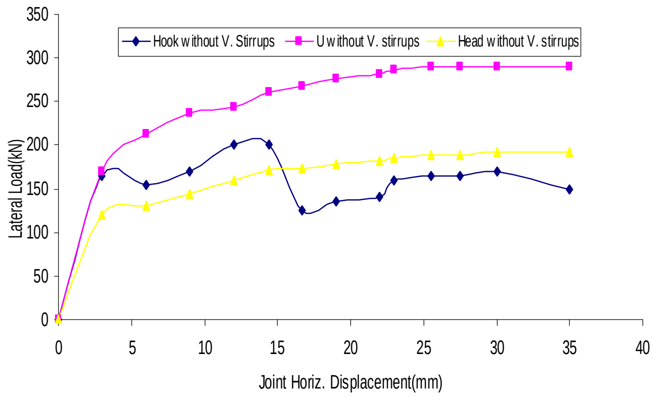


Figure 13 : Beam anchorage type effect on RC joint without vertical stirrups and improper column bars anchorage.

6 CONCLUSIONS

In this paper, the nonlinear ýnite element analysis software LS-DYNA is used to discuss the response of a RC inverted knee beam-column joint caused by event of a corner ground column loss. The results are summarized as follows:

- the concrete material model CSCM provides a proper material model for the complex behavior of concrete when only the most minimal information about the concrete, i.e. its unconfined compression strength, is known;
- selective mass scaling with some adjusted parameters is effective in reducing CPU required time with a small effect on model energy balance;
- U shaped beam bars end anchorage is better for progressive collapse resistance in terms of reducing joint rotation at beam joint interface and joint cracks; ductility was also improved by providing reinforcement continuity;
- adding joint vertical stirrups is more efficient with using headed end anchorage rather than the other two anchorage types.

In order to conduct a more accurate finite element analysis and to have a better representation of the physical problem, more research is needed on:

- more concrete material with easy input cards,
- the inþuence of selective mass scaling in increasing model resistance capacity and changing model energy balance as well.

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