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EVALUATION OF R.C. BEAM-COLUMN JOINTS UNDER CYCLIC LOADING USING ABAQUS AND DEEP LEARNING WITH PYTHON

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ABSTRACT: The beam-column connection has major roles in resisting lateral loads like earthquake, wind and blast. Undoubtedly keeping joints sustain through these loads performing on a structure will protect the human lives. For this specific reason, this research was carried out to investigate the beam-column connection by gathering the results from previous experimental researches. Those researches were executed an experimental trial on beam-column joint with different materials; such as Ferrocement and Carbon Fibre Reinforced Polymer, or using different types of stirrups like rectangle confining or spiral confining concrete. Theoretical analysis is operated using the Finite Element Software Abaqus, it is formulated considering the cyclic loading effects. The structural behaviour under cyclic loading like; energy dissipation capacity, stiffness degradation scaler, stress, compressive damage, tensile damage, displacements, equivalent plastic strain and plastic dissipation energy density are demonstrated. Comparisons with experimental results is accomplished to make sure that the finite element analysis is accurate. The parametric study is preformed to evaluate parameters by calculating errors, accuracy, and predict it is behaviour by Deep learning. At the end the correlations between these parameters are founded and presented by equations and the best reinforcing details with minimum errors is proposed.

Keywords*: cyclic loading, damage index, earthquake, reinforced concrete, beam-column joint, energy dissipation.*

1. INTRODUCTION

Transmission load between structural members is recognized as being one of the most critical design steps that designer should take into consideration. Loads transit from slab to beam then to the columns to deliver loads to the foundation, the foundation will transit it to the soil or rock. In some cases, assemblage of beam- column-slab transit loads to foundations, at this point we need to answer what the aim of design requirements?!, where the answer is "to produce members able to resist the specified gravity loads beside anticipated levels of an earthquake".

A beam-column joint has defined as the part of the deepest depth of the beam cross to the column, beam-column joint also classified into two categories according to ACI352R-02 [1]: Type 1 connection is composed of members designed to satisfy ACI 318-02. Type 2 connection, frame members are designed to have sustained Strength under deformation reversals into the inelastic range.

The previous definition for type 2 lead us to generate considerable interest to prevent beam-column joints type 2 from failure under Severe reverse cyclic loading especially lateral load such as seismic, blast & wind. Through achieving good ductility, good energy dissipation, and good self-cantering capacity of the structure, where energy dissipation capacity is considered the key parameter in resisting lateral loading. To permit structure from failure need to achieve two elements of structure capacity:

1-Min stiffness, K.
2-Min strength, fy.

Beam–column joint dissipate energy through reversals of deformation in inelastic range. Thus, it controls the achievement of good structure energy dissipation, also structure shouldn't pass ultimate capacity due to lateral load or the structure will fail. Being designers, our primary aim is to safe people life when random earthquake or blast happens, moreover is maintain important facility like (hospital and fire departments) work when these disasters happen.

2. LITRATURE REVIEW

Some studies tried to find numerical models that can help us understand the behavior of B-C joints under dynamic loads. Other studies try to use an analysis program to draw hysteretic loops to get results about best-detailing can resist dynamic loads and compare it with lab results. This section will Reviews some of these studies.

Venkatesan, et al. [2] studied seismic effect on exterior B-C joints strengthened with unconventional reinforcement detailing. Unconventional reinforcement refers to put Ferrocement on joints from one to two layers as well as tested on Experimental to get results such as displacement, stiffness & cumulative energy dissipation. In same time an analytical study carried out by finite element models using ANSYS program, where results show that Ferrocement samples has more energy dissipation capacity that needed for reinforced beam-column joints in seismic regions.

Ercan, et al. [3] researched on using fiber-reinforced plastics strengthening techniques. This research focus on studying Carbon fiber-reinforced plastic (CFRP). Placing these CFRP sheets internally and externally on various location on joints or whole sample. These Experimental tests are conducted by putting axial pressure on the column and hydraulic jack made displacement at the tip of the beam to get Joint failure load, displacement, beam failure, moment rigidity until first crack & energy absorption capacity. The most notable thing that this research proves that strengthen joints may increase ductility not capacity.

Azimi [4] examined different types of confining such as common closed stirrups (DCM- CONVEN), rectangular spiral reinforcement (DCM- SINGLE) & twisted opposing rectangular spiral (DCM- DOUBLE). An Experimental and Analytical analysis held.
Analytical analysis performed by ANSYS. This research seeks to get hysteresis response, Energy dissipation capacity, load-drift envelops, beam deflection, crack opening, Damage index [10] and tensile stresses in the joint rejoin. Results refer to the failure mode of RC beam-column connections is significantly affected by the angle between the shear reinforcement and shear cracks. DCM- DOUBLE and DCM- SINGLE specimens developing the higher capacity of the connected beam was observed. Rectangular spiral reinforcement gave a higher seismic performance. Finally, the DCM- DOUBLE specimen shows a higher energy dissipation capacity.

Cao, et al. [5] employed the experimental results to predict moment in beam-column connection by Extreme Learning Machine (ELM). Researchers investigated whether applying soft computing methods of the proposed beam to column connection in concrete frames can gain high nonlinearity. ELM proves as good static tool to predict moment in beam-column connection in concrete by getting same results as experimental one.

All previous researches aim to study the latest approaches without likening them together [11,14&15]. This is the goal of this study. Employing experimental results with finite element analysis and deep learning as statically tools to correlate between different parameters. Added to that the deep learning and ELM are differ, where deep learning depends on studying all hidden layers and ELM focus on one hidden layer.

3. METHODOLOGY

This study will depend on obtaining experimental data from previous researches for various specimens for different joints having different details and influenced by cycle loading. Consequently, insert these experimental data to finite element analysis program called Abaqus. The Abaqus analytical results will be compared with the experimental results to control margin of error between the two methods. Subsequently, apply those results (parameters) to Jupyter notebook which consider as a host environment for Python programming language. Furthermore, conclusion will be built base on results from deep learning and propose updated into design details.

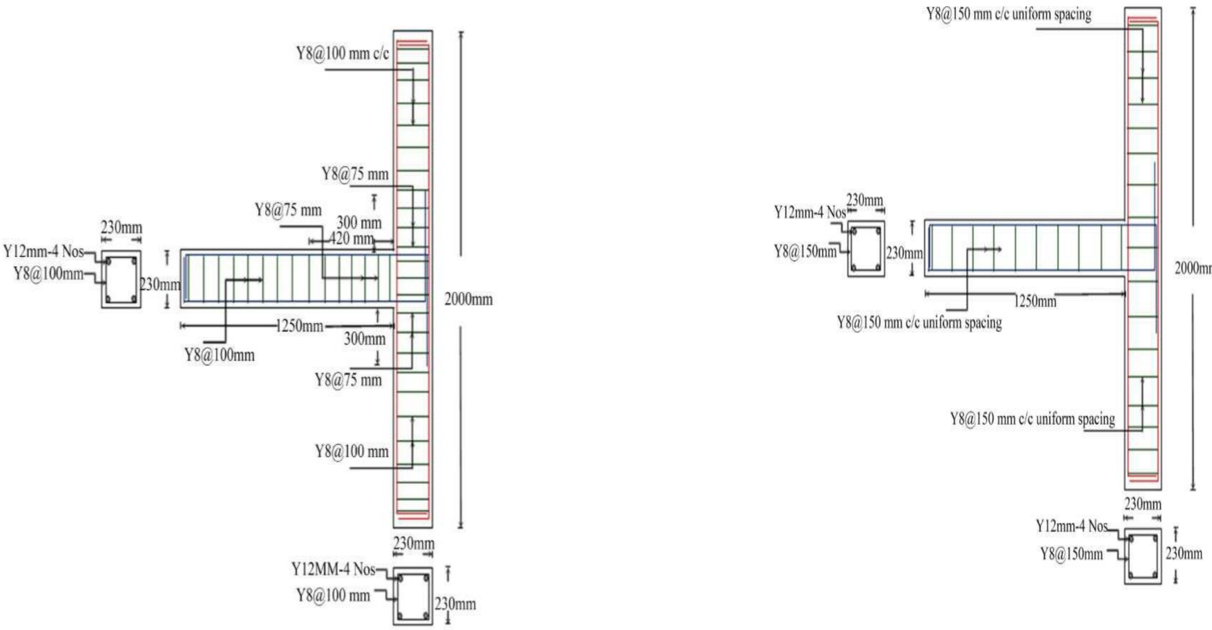
3.1 Collection of Data

The total number of Specimens are 13, divided into three main categories:

1- First category are 5 specimens (Non-Ductile ND-1, Ductile DD-1, Non-Ductile ND-T1, Non-Ductile-T2, Ductile-T1, Ductile-T2). The difference between ductile DD and noun ductile ND in specimens are spacing between strips in beam-column connection. Also, T1, T2 refer to numbers of layers of Weld mesh and Woven mesh in Ferrocement laminates at the beam-column connection, Venkatesan, et al. [2], see Fig.1 and Fig.2.

2- The second category are 5 specimens (Target, Control, Sample 1, Sample 2, Sample 3, Sample 4). Where target & control specimens have no CFRP on joints or members. Otherwise sample 1,3,4 have CFRP on beam-column joints or on member-only, sample 2 has diagonal bars on beam-column joints with no CFRP at all, Ercan, et al. [3], see Fig.3 to Fig.5.

3- The third category are 3 specimens different in stirrups (common closed stirrups DCM- Convene, rectangular spiral reinforcement DCM- Single and twisted opposing rectangular spiral DCM-Double Azimi, et al. [4], see Fig.6 and Fig.7.



(a) DD reinforcing details

(b) ND reinforcing details

Fig.1 Reinforcing details for category number 1

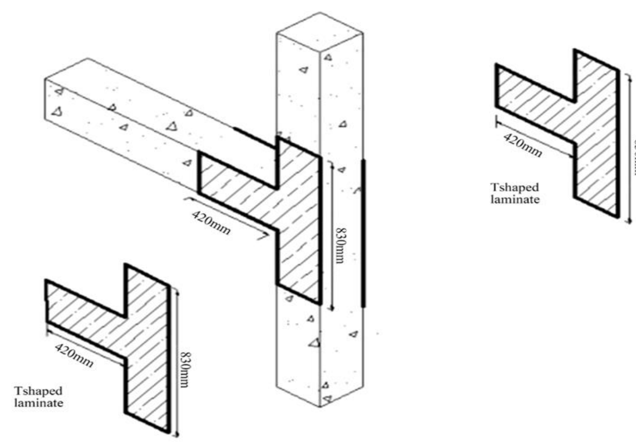
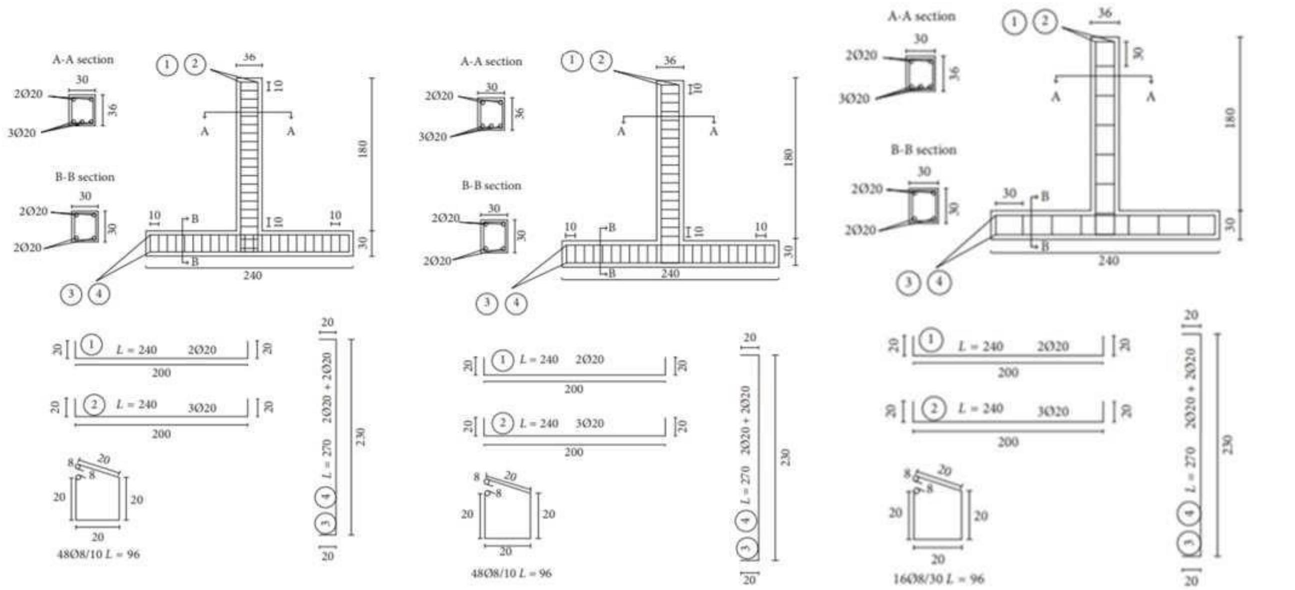


Fig.2 The detail of the Ferrocement laminates wrapping method.



(a) Target sample reinforcing details (b) Control sample reinforcing details (C) Sample (1 to 4) reinforcing details

Fig.3 Reinforcing details category number 2

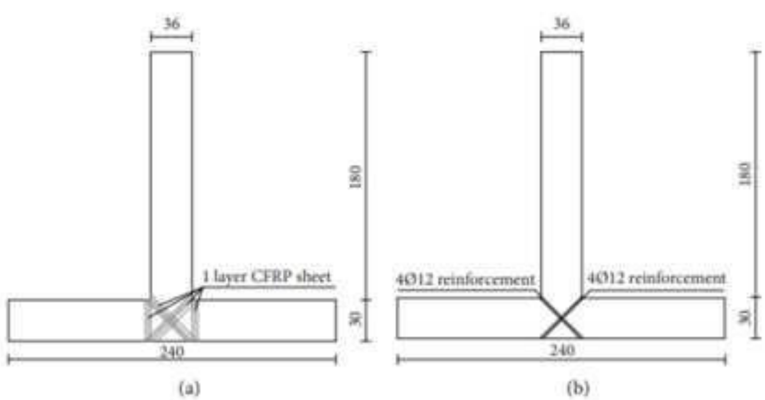


Fig.4 Schematic presentation of strengthening techniques: (a) Sample 1 and (b) Sample 2.

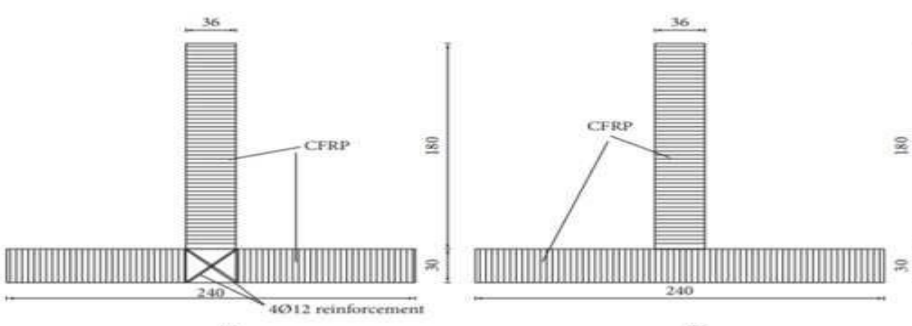


Fig.5 Schematic presentation of strengthening techniques (a) Sample 3 and (b) Sample 4.

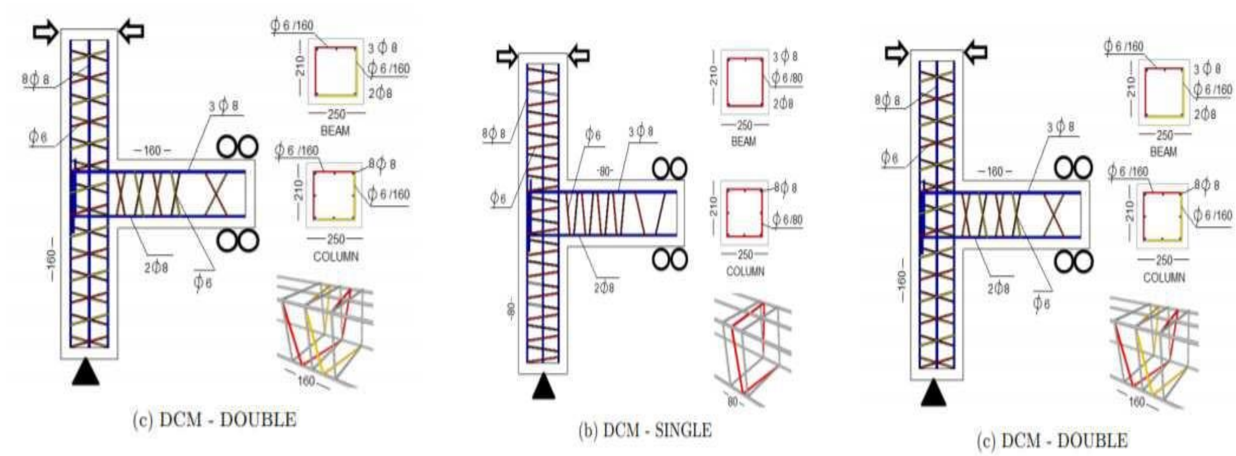


Fig.6 Reinforcing details for category (3)

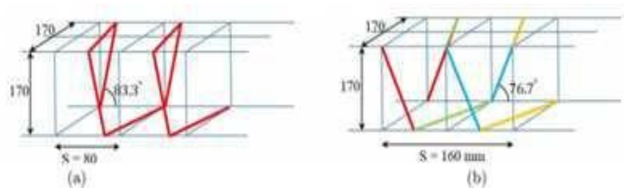


Fig.7 Application of (a) Single and (b) Twisted opposing rectangular spiral reinforcement in RC elements

The material properties of concrete to be employed in this investigation are, the compressive strength (fc) and the modules of elasticity (Ec) [16]. Additionally, the properties of steel are, the modules of elasticity (Es) and the yield stress (fy) for longitudinal and transverse steel. These material properties are listed in table 1.

Table 1 Material properties

Material properties	Concrete		longitudinal & transverse Steel	
	fc (MPa)	Ec (MPa)	Es (MPa)	fy (MPa)
Category 1	29	25419	200000	448
Category 2	30	25742	200000	420
Category 3	35	27805	200000	450

Unconventional methods are used in this research depend on adding CFRP and Ferrocement laminates in strengthen beam-column joints. A 2mm thickness bonding provided for Ferrocement laminates on beam- column joints are applied mention using (Corocretin IHL18), which is used for corrosion protection. The properties of CFRP sheets [13] employed in this investigation are:
(fy) = 3900 MPa , ultimate strength (fu) = 4100 Mpa , modulus of elasticity (E) = 230 GPa , A 0.166 mm CFRP sheets thick type Sika Wrap 300C.

The loading protocol (cyclic loading) data are presented graphs (Fig.8 and Fig.9) for categories 2 and 3. The graphs show a relation between load or drift ratio with the number of cycles. It should be noted that the study for category number one did not provide information about loading protocol or any graph [12].

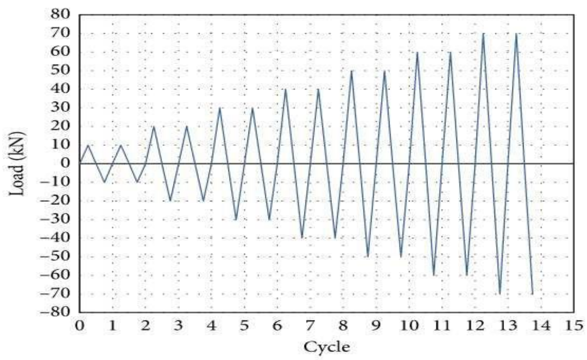


Fig.8 Loading protocol category 2

In columns the axial loads values are differ from one category to other. The values of the hydraulic jack loads applied on the tip of the beam to make the required displacement are listed in Table 2.

Table 2 Hydraulic jack loads

Category	1	2	3
Axial load (kN)	100	250	490
Hydraulic jack load (kN)	500	500	250

3.2. Finite Element Analysis

Finite element is known as a method for analysis structural frame by divided frame to nodes then arrange every node information in the matrix Logan [6]. A high nodes numbers could form an "Augmented Matrix". To solve equations results from these matrices might be by root-finding algorithms like the Newton–Raphson method. As a result, before using any analytical software it is preferred to review its manual theory for its finite element analytical methods.

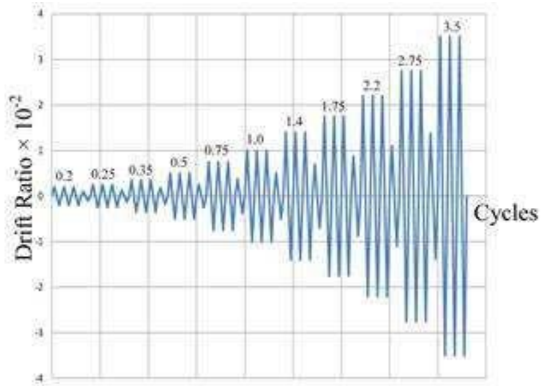


Fig.9 Loading protocol category 3

3.2.1. Finite Element Analysis theory

Equations Abaqus used for finite element analytical derived from equilibrium and virtual work methods. For dynamic analytical Abaqus used equivalent rigid body dynamic motion. Moreover, for Nonlinear solution methods in Abaqus the equilibrium equation as Abaqus manual following [16]:

$$F^N(u^M) = 0 \qquad (1)$$

Since it will be a large number of variables Abaqus using Convergence of Newton's method to ensure all entries are sufficiently small.

3.2.2. Finite Element Analysis ABAQUS

The most important step is to define boundary conditions and time. where matrix work depends on time. As much as you are accurate at this step and time fit your model no errors will appear [17]. There are three steps to program work on, step one is initial where there are no loads just to assign displacement as boundary condition. Step two is axial load on top of column. Step three is displacement at tip of column, see Fig.10, Najafgholipour, et al. [8].

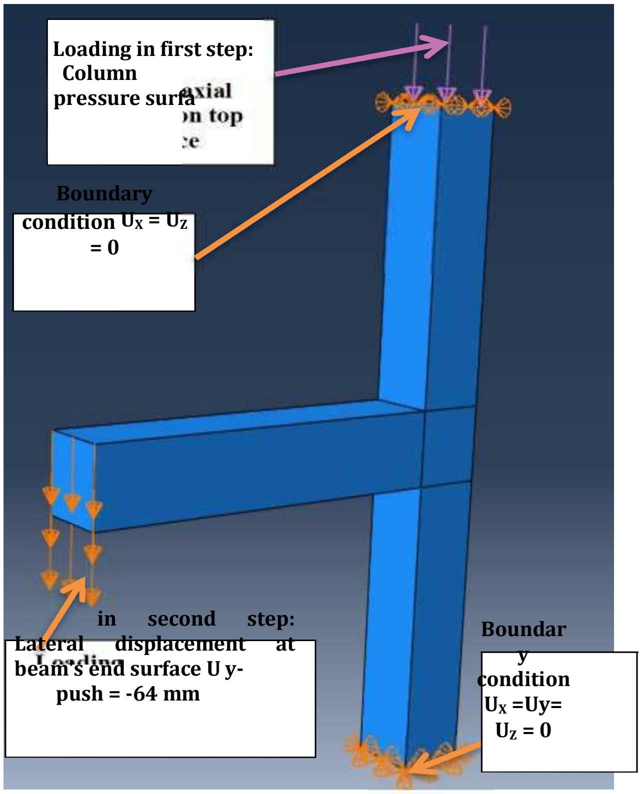


Fig.10 Simulated boundary conditions and loading of the specimen for exterior beam – column joint.

3.3. Deep Learning

Regression model established to perform for deep learning, require Python Anaconda, Juypter Notebooks and TensorFlow. The Juypter Notebooks is an environment which makes it easy to combine Python, Graphics and Text. Juypter
Notebooks needs to download google library
where can call mathematics functions. In addition to that, a high-level neural networks API (application 8programming interface) like Keras needed to complete sets for deep learning accurately.

4. RESULTS

4.1. Results from Abaqus

The following parameters are considered in the analysis: stiffness degradation scaler, stress, compressive damage, tensile damage, displacement and equivalent plastic strain.

4.1.1 Damaged reading

Table 3 displays the results of Tensile damage (DAMAGET), Compressive damage (DAMAGEC), Damage dissipation energy density (DMENER).

Table 3 ABAQUS CAE results damaged index.

Sample	DAMAGEC (Reading)	DAMAGEC (Ultimate)	DAMAGET (Reading)	DAMAGET (Ultimate)	DMENER (Reading)	DMENER (Ultimate)
ND-1	0.000719	0.000719	0.98	0.98	0.0067	0.0067
DD-1	0	0	0.98	0.98	0.00551	0.00551
ND-T1	0	0.809	0.98	0.98	0.00035	0.00769
ND-T2	0.05117	0.614	0.98	0.98	0.00033	0.006852
DD-T1	0	0	0.98	0.98	0.00551	0.00551
DD-T2	0	0	0.98	0.98	0.00551	0.00551
target	0.07457	0.89	0.98	0.98	0.0054	0.0054
control	0	0	0.98	0.98	0.0036	0.0036
sample 1	0	0	0.98	0.98	0.0011	0.001188
sample 2	0.024	0.024	0.98	0.98	0.0035	0.00358
sample 3	0	0	0.98	0.98	0.000403	0.000403
sample 4	0	0	0.98	0.98	0.00044	0.00044
DCM-CONVEN	0.127	0.5655	0.98	0.98	0.0106	0.0106
DCM-SINGLE	0.89	0.89	0.98	0.98	0.1142	0.1713
DCM-DOUBLE	0.8949	0.8949	0.98	0.98	0.2512	0.4307

Note: all parameters are unit less and these parameters are indicators values from zero to 1.

1- Tensile damage (DAMAGET) for samples in the table 3 reached its ultimate values and that expected hence concrete known as weak handling tensile stress.

2- Compressive damage (DAMAGEC) indicates that concrete has not damaged except these samples (DCM-SINGLE, DCM- DOUBLE, sample 2). For sample 2 and

DCM- SINGLE have common reinforcing detail. For DCM- DOUBLE has rectangular spiral confining that cause increase in compressive stress which concrete could not handle it.

3- Damage dissipation energy density (DMENER) indicates that joints have reached it is ultimate value [9] except (ND-T2, DCM- SINGLE, DCM- DOUBLE) where these three samples were good at handling damage.

4.1.2 SDEG, Displacement and S readings

Table 4 displays the results of Scaler Stiffness Degradation (SDEG), displacement, stress (S, miss).

Table 4 ABAQUS CAE results; (SDEG), displacement and (S).

Sample	SDEG Reading	SDEG Ultimate	Displacement Reading (mm)	Displacement Ultimate (mm)	S, miss Reading	S, miss Ultimate(
ND-1	0.98	0.98	29	91.6	10.1337	448
DD-1	0.98	0.98	39	89.18	7.36	448
ND-T1	0.158	0.993	39.9	143.7	4.63	448
ND-T2	0.13	0.9923	46	110.06	12.33	448
DD-T1	0.98	0.98	44	89.19	9.91	447.3
DD-T2	0.98	0.98	44.5	89.1	9.91	447.3
target	0.98	0.98	21.8	78.15	4.99	431
control	0.98	0.98	17.5	69.4	8.65	435.6
sample 1	0.98	0.98	40.93	69	10.82	370.1
sample 2	0.98	0.98	30	70	7.77	428.7
sample 3	0.9796	0.9796	47	70	5.19	171.6
sample 4	0.979	0.9796	42	70	5.233	169.7
DCM- CONVEN	0.98	0.9844	36.15	144.6	8.33	448
DCM- SINGLE	0.9	0.9	29.66	178	28.79	448
DCM- DOUBLE	0.8982	0.8982	35.2	210.1	40.35	448

Note: SDEG is unit less parameter which indicate values from zero to 1.

1-Scaler Stiffness Degradation (SDEG) values reached ultimate except (ND-T1, ND-T2).

2-Lowest displacement value shown sample (control) and higher value shown sample (ND-T2).

3- Both ultimate displacement & ultimate stress has not been reached by any of the samples.

4.1.3 PEMAG, PENER Reading

Table 5 displays the results of Magnitude of Plastic Strain (PEMAG), Plastic Dissipation Energy Density (PENER).

Table 5 ABAQUS CAE results; PEMAG and PENER

Sample	PEMAG (Reading)	PEMAG (Ultimate)	PENER Reading (N.mm)	PENER Ultimate (N.mm)
ND-1	0.3134	0.3134	10.3	124.3
DD-1	0.2948	0.2948	9.99	119.9
ND-T1	0.00453	0.543	23.34	280.1
ND-T2	0.03986	0.4783	20.75	249
DD-T1	0.2948	0.2948	9.995	119.9
DD-T2	0.2948	0.2948	9.995	119.9
target	0.226	0.226	7.298	87.47
control	0.221	0.221	6.983	83.8
sample 1	0.03187	0.03187	0.7442	8.931
sample 2	0.2532	0.2532	7.271	87.25
sample 3	0.001342	0.001342	0.001282	0.001282
sample 4	0.001338	0.001338	0.001278	0.001278
DCM- Convene	0.3641	0.3641	17.8	213.7
DCM- Single	0.072378	0.5976	25.3	304.5
DCM- Double	0.05	0.7445	31.62	379.4

Note: PEMAG is unit less parameter.

1- Four samples (ND-T1, ND-T2, DCM- SINGLE, DCM-DOUBLE) have not reached ultimate values for Magnitude of Plastic Strain (PEMAG).

2- Plastic Dissipation Energy Density (PENER) for samples reached highest values for sample (DCM-DOUBLE) while lowest values are for samples (sample 3 and sample 4). it must be noted that high Plastic Dissipation Energy Density (PENER) value refer to good sample handling energy.

Table 6 ABAQUS CAE and Experimental displacements results

Sample	Displacement Experimental (mm)	Displacement ABAQUS (mm)	Error (%)
ND-1	30	29	3.45
DD-1	40	39	2.56
ND-T1	40	39.9	0.25
ND-T2	45	46	2.17
DD-T1	45	44	2.27
DD-T2	45	44.5	1.12
target	22.38	21.8	2.97
control	17.66	17.5	0.91
sample 1	40.1	40.93	2.028
sample 2	32.4	31.2	3.9
sample 3	47.85	47	1.81
sample 4	43.44	42	3.43
DCM-Convene	-	36.15	–
DCM-Single	-	29.66	–
DCM-Double	-	35.2	–

4.2 Results from Python

Finding the relationships between parameters and errors for each sample is by convert data (input) to Z-table to minimize errors presented in table 8. Afterward, python takes two value from samples for the same parameter where one called X_test, other called X_train. Wherever python attempted to obtain a correlation that contributed a values closer to x-test values. The correlations founded for different parameters are presented in the following sections.

4.2.1 Displacement

The main equation to predict displacement value at certain values.

A- Main Equation

Dis = (m1*DAMAGEC) +(m2*DMENER) + (m3*SD) + (m4*En) + (m3*stress) + (m4*PEM) + (m5*PENER)

Dis = (-1.68347617*DAMAGEC) + (1.99301209*DMENER) + (0.60372591*SD) - (0.69159869*En) + (0.31516317*stress) - (0.32346632*PEM) – (1.01870836*PENER) + (-3.4433235646925584e-17)

B – from main equation trying to predict Displacement value from main equation at these certain value PENER =0.114826, PEM= 1.130131, stress= -0.156943, En =-1.059612, SD= 0.434970, DMENER= -0.317847, DAMAGEC = -0.458584 is equal = 0.07676977

C- Training value and test value models error percentage for first trial and next trial are listed in table 8.

4.1.4 Variations between ABAQUS and Experimental results

Table 6 illustrates the variations between ABAQUS CAE and experimental displacements results. Table 7 illustrates the variations between ABAQUS CAE and experimental energy dissipation capacity results. Error percentage are not higher than 4%, which is considered a satisfactory value.

Table 7 ABAQUS CAE and ExperimentalEnergy Dissipation capacity results

Sample	Energy Dissipation capacity - TEST (N.mm)	Energy Dissipation capacity - ABAQUS ((N.mm))	Error (%)
ND-1	1032	1000	3.17
DD-1	989	980	0.95
ND-T1	2897	2900	0.087
ND-T2	2734	2700	1.247
DD-T1	2734	2700	1.247
DD-T2	3947	3897	1.278
target	37669	37000	1.808
control	11322	11000	2.931
sample 1	23697	23000	3.029
sample 2	15092	15000	0.614
sample 3	11882	11500	3.324
sample 4	1032	1000	3.167
DCM-Convene	10000	10100	0.990
DCM-Single	26100	25500	2.353

Table 8 Training value and test value models error percentage.

X_train	X_test	Error (%)
-0.68581384	0.6840111	0.263
-0.7378104	-0.7035249	4.647

D- degree of error (Loss)
loss: 0.0799, val_loss: 5.4023e-04
E- Final score Mean Square Error (MSE) = 0.00079506 (0.079%)
F- Final score Root Mean Square Error (RMSE) = 0.028 196(2.81%)
G-the following chart Fig.11 shows two lines one re-presents predict values and other Shows expected value after training model

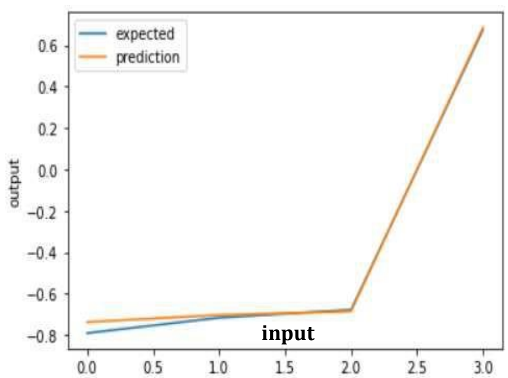


Fig.11 The variations between predict values and expected for displacements.

4.2.2 Displacement and Ultimate Displacement To find relation between ultimate Displacement and displacement same as before first enter input data. Then convert it to Z-table.

A- Main Equation
Ultimate Displacement = (m1*Displacement) + b
Ultimate Displacement = -0.00272* Displacement + 1.48309e-16
B- degree of error (Loss)
loss: 0.0084, val_loss: 0.0044
C- Final score Mean Square Error (MSE) = 0.005204 (0.5204%)
D- Final score Root Mean Square Error (RMSE) = 0.0721 (7.21%)
E-the following Fig.12 shows two lines one represent predict values and other Shows expected value after training model

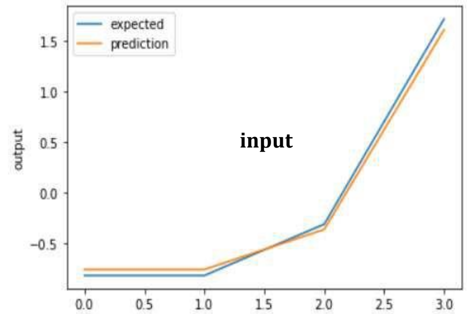


Fig.12 The variations between predict values and expected for ultimate displacements.

4.2.3 Displacement and Plastic Dissipation Energy Density (PENER)
To find relation between plastic dissipation energy density (PENER) and displacement same as before first enter input data. Then convert it to z-table.

A- Main Equation
Dissipation Energy Density (PENER) = (m1*Displacement) + b

Dissipation Energy Density (PENER) = 0.0831* Displacement + 1.1e-16
B- degree of error (Loss)
loss: 0.8223, val_loss: 0.0011
C- Final score Mean Square Error (MSE) = 0.00164 (0.164%)
D- Final score Root Mean Square Error (RMSE) = 0.0405 (4.05%)
E-the following Fig.13 shows two lines one represents predict values and other shows expected value after training model

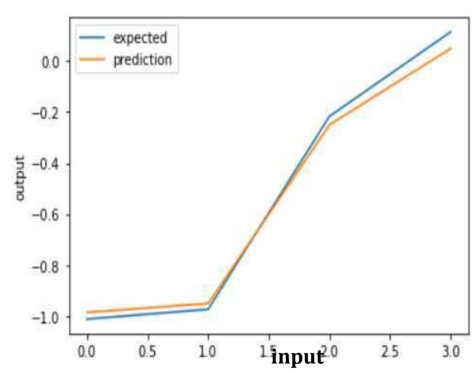


Fig.13 The variations between predict values and expected for (PENER).

5. CONCLUSIONS

1- The variations error percentages between ABAQUS CAE and experimental displacements and experimental energy dissipation capacity results are not higher than 4%, is believed a satisfactory value.

2- DCM- Double and DCM- Single samples presenting a good handling for damage dissipation energy density (DMENER). Magnitudes of plastic strain (PEMAG) and plastic dissipation energy density (PENER) produced highest stresses values.

3- The samples ND-T1and ND-T2 afforded the lowest scaler stiffness degradation (SDEG) values.

4- Employing the artificial intelligence (AI) by deep learning can help to build equations binding all parameters within minimum errors. The correlations involving different parameters; displacement, ultimate displacement and dissipation energy density are founded.

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