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Neuro solution for damage detection and categorisation of earthquake-affected buildings

V.S. Purani and S.C. Patodi

To assess structural damage to reinforced concrete (RC) framed buildings due to an earthquake a neural network approach is recommended in this "Point of View". Training patterns are generated based on different types of damage observed in columns, beams, floors, staircases, lift shell walls, etc, using field data collected in the earthquake of 26th January 2001 in Ahmedabad city. About 150 framed structures including low- and high-rise buildings were surveyed and more than 900 training patterns were generated for training six different counterpropagation networks. The trained networks suggest the category of a damaged building, with suitable post earthquake action.

Categorisation of earthquake-affected buildings is normally done by inspecting damages in various engineering and non-engineering building elements. Columns, beams, lift shells and slabs, etc, are grouped by engineering elements, while partition walls and stair flights-landings, etc, are considered as non-engineering building elements. After an earthquake, when the number of damaged framed structures is large, their damage categorisation is a huge task and requires a tremendous effort of sound technical judgement. Also, it is essential to have uniformity in categorisation, as the same is carried out by a number of structural engineers.

During the recent earthquake of Gujarat, the authorities received more than 6000 applications in Ahmedabad city itself from occupants of buildings requesting categorisation of their buildings at the earliest. Staff members of the municipal corporation and technical institutes, along with consulting structural engineers, carried out this job on a war footing. Even then the occupants were impatient about the delay and ambiguity in the categorisation. During the process of evaluation of the type of damage to the buildings, a need for a powerful software was felt, which could carry out such work rapidly and accurately. In this context, the use of artificial neural networks (ANN) is considered here as one of the most promising techniques, because ANN has the capability to directly use the available field/practical results for clustering, mapping and classifying input and output in the absence of any mathematical relationship. Among the available networks, the counterpropagation neural network (CPN) algorithm used in this work is unique in its capabilities[1-2]. Its separate supervised and unsupervised learning with fixed network architecture and parameters offers an excellent and fast convergence during training and accurate prediction at the time of testing. In this paper, an innovative concept for prediction of damage category and post-earthquake actions for distressed building, is implemented by developing six CPNs, one for each different building element. The training data sets are generated from actual inspections of the damaged buildings and to after training the network, the CPN is used to predict the damage category of the building and suggest remedial measures. The power of micro foundation classes (MFC) is exploited and an interactive graphical user interface (GUI) is developed in the present work under a visual C++ environment to facilitate input and output.

Categorisation of damages due to earthquake

Visual inspection of a damaged building by a structural engineer involves rigorous study of all building elements.

Depending upon the type of structural component, the following modes or patterns of damage/cracks are significant and play an important role in determining the building category after an earthquake.

Columns

An earthquake has the maximum effect on a column element when a framed structure is provided with a hollow plinth, that is, open parking below the elevated first floor. In this case, columns at the ground floor level show more damage compared to the upper floor levels. Building geometry, column location and its orientation, tie beam at plinth level and properties of the footing are a few parameters responsible for the degree of damage to the column. Depending upon the location of the column, the columns can be grouped in four categories: corner columns, columns near stairs, peripheral columns and interior columns. Most commonly, columns of different groups are found with different damage patterns such as horizontal cracks near beam-column junction, inclined cracks at 45° to the horizontal, vertical cracks, buckling of the bars and crushing of the concrete.

As per guidelines provided by Arya, *Table* 1, if 40 to 50 percent of the columns are damaged with very fine cracks, building falls in G1 category and these cracks are to be replastered[3]. If 40 to 50 percent of the columns have cracks up to 1 mm wide and the rest of the columns are in G1 category, then the building is considered to be in G2 category. After removing the plaster, cracks are to be grouted with epoxy or similar materials. Building falls into G3 category if 40 to 50 percent of the columns are damaged with cracks up to 2 mm wide but without relative movement between the two ends, and the rest of the columns are in G2 category. In this case, the building needs to be vacated, and reoccupied only after seismic restoration and strengthening. If crushing of the concrete, buckling of the bars, relative movements in parts of column and floor, wide inclined cracks, etc, occur in 40 to 50 percent of columns, then the building is categorised as G4. It needs to be vacated immediately and it would have to be either demolished or extensive restoration work would have to be carried out before reoccupation. When a large part of the building collapses and it is no more usable, it is considered to be in G5 category.

Beams

Compared to columns, less damage has been observed in beams in an earthquake. However, a large number of cantilever beams supporting stub columns were found distressed in the recent earthquake with, shear cracks at about 45° near support. Cantilever, peripheral and inner beams were observed for inclined shear cracks near support, vertical cracks near mid-span and horizontal cracks. Damage to the beams alone without damage to the columns was rarely found and hence categorisation of the building should be mainly governed by the severity of the damage to the columns. However, categorisation as per the damage intensity of the beams can be considered in a manner similar to that in the case of columns.

Floors

Slabs offer significant resistance to earthquake forces, but due to damages in beams and columns, slabs also get damaged. The floors, for damage categorisation purposes, were observed to be in four groups, that is, ground floor, first floor, second floor and all upper floors together. Cracks,

Table I : Categorisation of RC framed buildings damaged in cities of Gujarat during earthquake on January 26, 2001[3]

Category	*Damage*	*Extent of damage in non-engineered component*	*Extent of damage in RC column*		*Suggested post-earthquake action*
			Individual column	*All column in ground storey*	
0	None	No damage	No damage or visual cracks	No damage	Seismic strengthening is required for long-term seismic safety
G1	Slight non-structural	Thin cracks in plaster, falling of plaster bits in limited parts	Very fine cracks in columns, which are to be seen with much attention	40 to 50 percent of columns with G1 rest in category 0	Remove plaster across crack and replaster. Building need not be vacated Seismic strengthening is required for long-term seismic safety
G2	Slight structural	Small cracks in wall, falling of plaster in large bits over large area, damage to non-structural parts like chimneys, projecting cornices, etc. The load carrying capacity of the structure is not reduced appreciably	Wider cracks in column approaching 1 mm width going through core of column, visible to eye	40 to 50 percent in G2 rest in category G1	Remove plaster and grout cracks using epoxy or similar materials. Building need not be vacated. Seismic strengthening is required for long-term seismic safety
G3	Moderate structural damage	Large and deep cracks in walls, wide spread cracking of walls, columns and piers and tilting or falling of chimneys. The load carrying capacity of structure is partly reduced	Cracks in column at top and within height approaching 2 mm width with some crushing of concrete at the cracks but without relative movement between two parts	40 to 50 percent in G3 rest in category G2	Building needs to be vacated. To be reoccupied after restoration and strengthening Seismic strengthening is required for long-term seismic safety
G4	Severe structural damage	Gaps occur in walls, inner or outer walls collapsed, failure of ties to separate parts of buildings. Approximately 50 percent of the main structural elements fail. The building takes a dangerous state	Diagonal cracks/torsional cracks/ substantial crushing of concrete, buckling of reinforcement, 'through' wide cracks in column including relative movement in parts of column and floor	40 to 50 percent in G4 rest in category G3	Building needs to be vacated. Either building has to be demolished or extensive restoration and strengthening work has to be carried out before reoccupation.
G5	Collapse	A large part or whole of the building collapses	A large part or whole of the building collapses		Cleaning the site and reconstruction

delamination and spalling are three major possible types of distress in the slab concrete.

Stairs

Stair flight and landing are observed for the cracks either along the flight or perpendicular to the flight. If the stair flight is attached to the wall originally, its separation from the wall should also be observed.

Lifts

Inspection for damages in lift walls, made up from reinforced concrete, brick or columns with brick infill, is to be made mainly for vertical cracks, diagonal cracks, spalling of concrete, etc. To decide the category, the damage to the RC lift shaft is to be inspected carefully, because the wall of this shaft behaves as a shear wall, which is one of the major structural components of the building.

Damages in walls

Load bearing walls in some parts of a framed structure and other internal and external partition walls are generally affected with vertical, horizontal, diagonal, toothing and cross type cracks. These cracks are either thin or wide and may be through and through. Individual categorisation of the damage is to be made based on the type and intensity of the damage.

Damage intensity

It may be noted here that after completing the damage assessment of the individual structural components, as per the guidelines given by Arya, their damage intensity is broadly classified as

- *(i)* none
- *(ii)* minor non structural cracks
- *(iii)* minor structural cracks
- *(iv)* moderate cracks
- *(v)* large cracks
- *(vi)* crushed concrete

and respective post-earthquake actions are suggested accordingly[3]. In the training pattern for each building component, as shown in *Table* 1, the output pattern consists of damage category and suggestion number. For example, for the column, suggestion code number C-0, C-1, C-2, C-3, C-4, C-5 respectively correspond to the above six classes of damage intensity. Each suggestion number includes about three to four post-earthquake actions as given by Arya[3]. The network predicted suggestion number is then interpreted for individual group of components and the most severe suggestion code among all was finally suggested for the building. However, the measures suggested by the network may be considered as guidelines and needs to be confirmed based on engineering principles before deciding on the actual repair action.

Neuro solution for damage category

For the present work, an innovative concept of multi-network was investigated by developing six CPNs functioning in parallel. Each network was trained for patterns generated from actual field observations and categorisations made for earthquake-affected buildings in Ahmedabad city. Guidelines provided by Arya in this respect is helpful, especially in case of columns and these guidelines have been used[3]. The prepared networks were flexible enough to add any new training patterns, up to a total of 3000 training sets. For verification purposes, for each CPN, an interactive GUI-based dialogue was developed for the data input. Help buttons provide all necessary information to the user about the input for the respective CPN dialogue box. After having been assigned all input data, testing patterns for the respective CPN are generated and using the stabilised weights of the CPN, two outputs are obtained. The first output is damage category for the respective building component and the second is post earthquake action for the same. Some sample training patterns, for each CPN, are presented in *Table* 2. Network formulation for training and testing aspects of these CPNs is described below.

CPN for column

A CPN was created with four nodes on the input layer representing the percentage of columns damaged in each group. Percentage damage to the corner columns, peripheral columns, columns near stair and internal columns were obtained for the various types of damages to the column group. There were two output neurons which represent category of damage to the columns and the desired post earthquake actions. A total of 364 training patterns were compiled for 4-364-2 CPN architecture using the actual field data and available guidelines for building categorisation. For post earthquake actions, depending upon the type of damage to the different group of columns, suggestions were prepared and were included in the training data sets with their identification number.

CPN for beam

Five nodes in this CPN were designed to receive the response in terms of percentage damage. Damages to peripheral, stub column-supporting cantilever and inner beams at first floor level were assigned to the first three nodes whereas the last two nodes represent percentage damage to all upper floor beams in peripheral and inner beam groups. A CPN architecture 5-292-2 was used with 292 competitive nodes in the hidden layer.

CPN for floor

Cracks, delamination and spalling of the concrete in slabs were three inputs for the CPN of 3-143-2 architecture. Ground floor, first floor, second floor and all other upper floors together for a damaged building were observed for these three types of damages. 143 training patterns were prepared for different damage combinations and post-earthquake action. For a specific input pair element, numbers 1 and 0 were used for damage and no damage condition respectively. Thus, for a particular damage, a number between 0 and 4 in the input pattern represent cumulative distress of floors observed in four stages.

CPN for stair

A 3-15-2 network architecture was used with input neurons designed to receive responses for distressed staircase and landing. The first input neuron receives distressed condition in perpendicular direction for both stair and landing. The second neuron is similarly meant for perpendicular cracks along them. Condition for separation of stair from wall was taken as input to third neuron. Any number from 0, 1 and 2 is possible as first two inputs while third input of separation of stair from wall is simply taken as a Boolean number.

CPN for lift

For this CPN, only a limited number of training patterns were available. A CPN with 4-12-2 topology was trained for vertical cracks, diagonal cracks, and spalling of wall material as three types of observed damages. The first input was the type of lift shaft; numbers 1, 2 and 3 was taken for RC wall, beam-column frame with infilling brick wall and brick wall alone, respectively while Boolean number, were used for the three types of damage as the second, third and fourth input.

CPN for wall

Load bearing and partition walls were observed separately for thin and wide cracks. Out of the eight nodes selected for input, the first four nodes represented the damage to load bearing walls while the others were for partition walls. The crack type which may be vertical, horizontal, diagonal, toothing or cross was observed for thin or wide size. In total, ten types of damage to a wall were grouped into four as thin-wide vertical-horizontal cracks and six as thin- wide diagonal- cross- and toothing cracks. For a damaged building, all the ten observations were taken for load bearing, external and internal partition walls.

To test the performance of the trained networks, an unknown damaged building, which was not included in the

Table 2: Sample training patterns for CPNs

CPN for column

Sr no	Percentage of damaged columns at: Corner	Peripheral	Near stair	Inner	Category no	Suggestion no
1	20	0	20	20	G2	C-2
2	0	0	90	30	G3	C-3
3	10	20	20	30	G1	C-1
4	90	100	60	60	G4	C-4
5	100	100	100	100	G5	C-5

CPN for beam

Sr no	Percentage of damaged beams at					Category no	Suggestion no
	First floor			Upper floors			
	Peripheral	Stub column	Inner	Peripheral	Stub column		
1	60	60	40	40	40	G3	B-3
2	40	0	0	0	0	G2	B-2
3	0	10	20	20	10	G1	B-1
4	100	95	100	90	100	G5	B-5
5	80	95	85	70	50	G4	B-4

CPN for floor

Sr no	Cracks	Delimination	Spalling	Category no	Suggestion no
	GF, FF, SF, upper floors- 1: Damage; 0: No damage				
1	1 + 1 + 0 + 0	0 + 0 + 0 + 0	0 + 1 + 0 + 0	G1	F-1
2	0 + 1 + 1 +1	1 + 1 + 1 + 1	0 + 1 + 0 + 0	G3	F-3
3	1 + 1 + 1 + 0	1 + 1 + 0 + 0	1 + 0 + 0 + 0	G2	F-2
4	1 + 1 + 1 + 1	1 + 1 + 1 + 1	1 + 1 + 1 + 1	G5	F-5
5	0 + 1 + 1 + 0	1 + 1 + 0 + 0	0 + 1 + 1 + 1	G4	F-4

CPN for stair

Sr no	Parallel to flight	Perpendicular to flight	Separation from wall	Category no	Suggestion no
1	1 + 0	0 + 1	0	G2	S-2
2	0 + 0	1 + 0	1	G1	S-1
3	1 + 1	1 + 1	1	G3	S-3
4	0 + 0	0 + 0	0	G0	S-0

CPN for lift

Sr no	Types of cracks observed: Lift type	Vertical	Diagonal	Spalling	Category no	Suggestion no
1	1; RC wall	1	1	0	G3	L-3
2	2: Brick wall	1	1	0	G2	L-2
3	3: Column + wall	0	1	0	G1	L-1
4	1: RC wall	1	0	1	G3	L-3
5	3: Column + wall	0	0	1	G2	L-2

CPN for wall

Sr no	Number of damaged walls (external + internal) at								Categ-ory no	Sugges-tion no
	Load bearing wall				Partitioning wall					
	Thin		Wide		Thin		Wide			
	V	H	V	H	V	H	V	H		
1	1	0	0	1	1	0	1	1	G1	W-1
2	1	1	1	0	0	1	1	0	G2	W-2
3	2	2	2	2	2	2	2	2	G4	W-4
4	2	1	2	0	0	1	2	1	G3	W-3

Note: V = Vertical; H = Horizontal

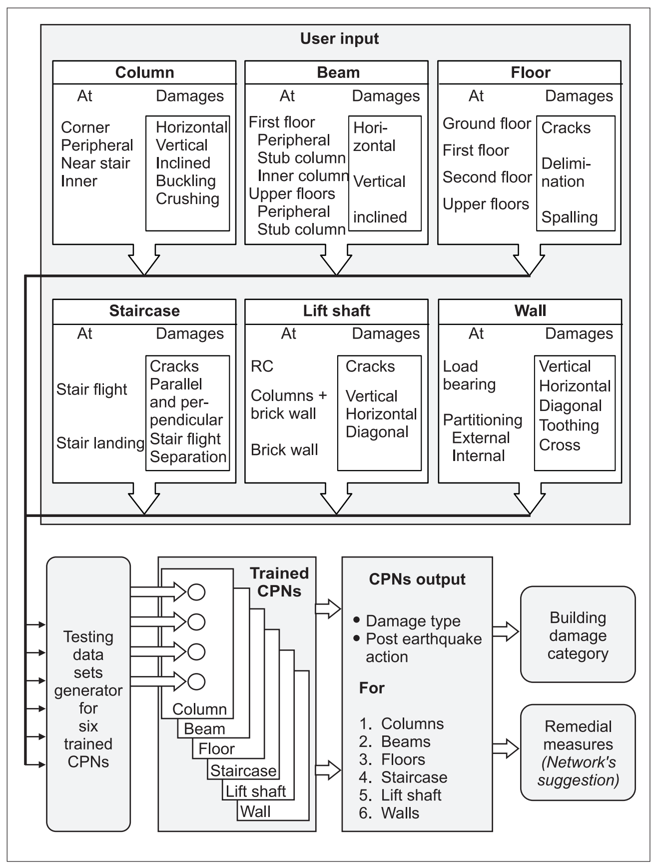

Fig 1 Flow of information through different CPN models

training, was taken. Data on damage to the various elements are assigned to the respective CPNs one by one as shown in *Fig* 1. After an interactive user input, testing data sets were generated for different CPNs and then trained CPNs predicted the damage category and gave suitable suggestions for distressed building elements. In this process, the number of winning nodes in the competition layer was set to one so that only the nearest node in terms of eucledean distance would be selected from the stabilised weight vector and hence output fired by this node would be available without any interpolation. *Figs* 2 to 7 show GUI based input to the different CPNs. The output sheet generated by the network gives summary of damage to the different structural elements as shown in *Fig* 8. The network, as per its predicted damage category, assigns damage status to the individual element as shown in the *Fig* 9. The required post earthquake action can be availed by clicking the suggestion button provided separately for each building component as shown. Based on the severity of the damage status of different elements of the

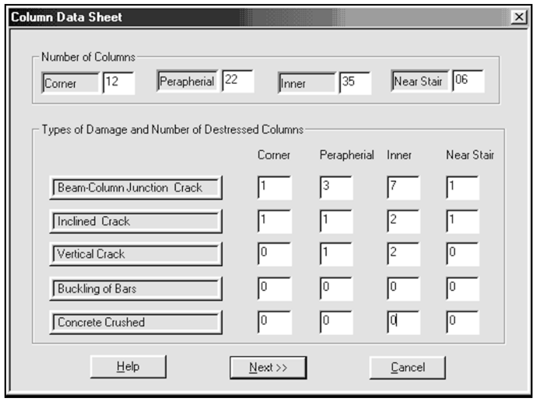

Fig 2 Input data form for column CPN

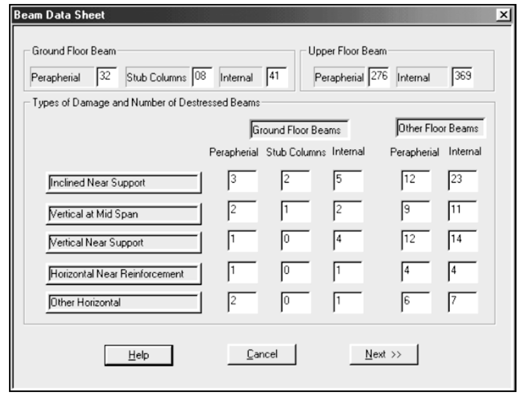

Fig 3 Input data form for beam

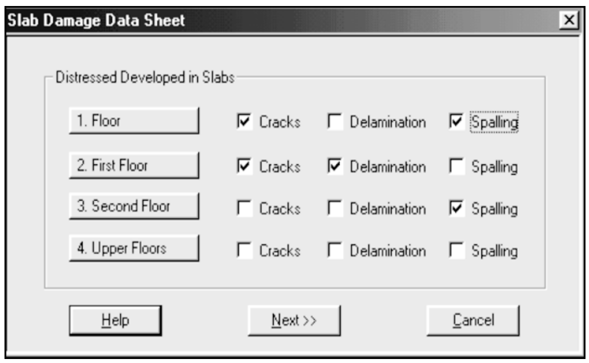

Fig 4 Input data form for floor CPN

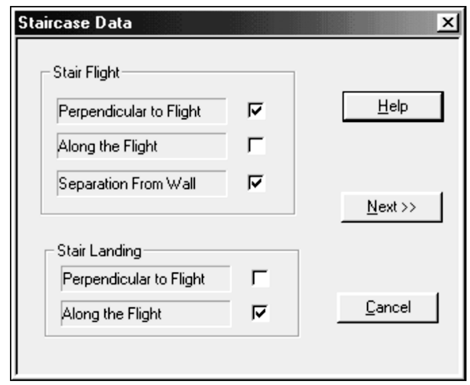

Fig 5 Input data form for staircase CPN

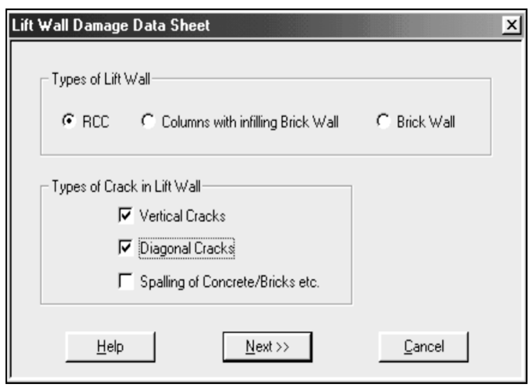

Fig 6 Input data form for lift shaft CPN

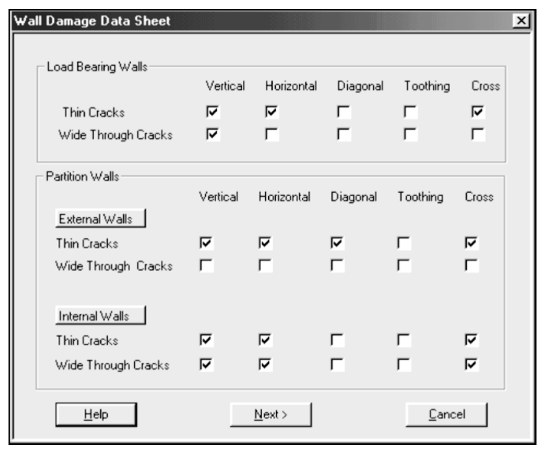

Fig 7 Input data form for wall CPN

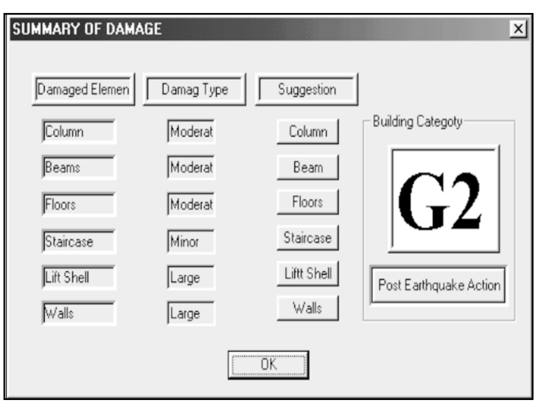

Fig 8 An output sheet generated by network

Fig 9 Suggestion offered by network

building, the final damage category of the building was decided.

Conclusions

Damage assessment for earthquake-affected framed buildings for categorisation and post-earthquake action was automated by means of an innovative approach using neural networks. Although many possible types of damage to the engineering and non-engineering building components were taken in to account, the prepared networks were flexible enough to add any new training patterns up to a total of 3000 training sets for training the six different CPNs.

The performance of the networks was examined for various unknown cases and found in agreement with the actual categorisation of the damaged buildings. It has been observed that the CPN with one winning node is able to categorise the damaged building accurately.

The suggested CPN based multi-network approach seems to be the fastest and most consistent approach for predicting the damage category and suggesting remedial measures for earthquake-affected buildings.

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Dr S.C. Patodi is professor of structural engineering and head of applied mechanics department at the Faculty of Technology & Engineering, Baroda. He obtained PhD from the Indian Institute of Technology Mumbai and has guided 48 ME dissertations and has published 112 research papers. He is recipient of 5 best research paper awards.

Mr Vinay S. Purani obtained his masters degree in civil engineering from Gujarat University in 1996. He has worked with HBJ Gas Project in the construction of gas based power plant. Presently, he is working at Government Engineering College, Modasa and is also a registered research scholar of applied mechanics department at Faculty of Technology and Engineering, Baroda. He has published 15 papers

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