International Journal of Engineering Trends and Technology
ISSN: 2231–5381 / https://doi.org/10.14445/22315381/IJETT-V71I4P239

Volume 71 Issue 4, 462-473, April 2023

Original Article

Finite Element Modelling of Corroded RC Flexural Elements

Anil Kumar[1*], Anil kumar chhotu[1], Ghausul Azam Ansari[1], Md. Arman Ali[1], Abhishek kumar[2], Rajkishor[3], Ashutosh kumar[4]

[1]*Department of Civil Engineering, Motihari College of Engineering, Motihari, Bihar, India*
[2]*Department of Civil Engineering, Government Engineering College, West Champaran, Bihar, India*
[3]*Department of Civil Engineering, Bhagalpur College of Engineering, Bhagalpur, Bihar, India*
[4]*Department of Mechanical Engineering, Motihari College of Engineering, Motihari, Bihar, India*

[*]*Corresponding Author : anil.20688@mail.com*

Received: 25 November 2022 Revised: 30 March 2023 Accepted: 13 April 2023 Published: 25 April 2023

Abstract *- One of the frequently seen phenomena is the corrosion of rebar in reinforced cement (RC) elements. Rebar corrosion impacts how well RC structures work and ultimately causes the structures to fail. In this paper, the residual flexural capacity of RC beams is evaluated by an analytical approach and finite element analysis. Residual bond strength is required for the analytical calculation of residual flexural capacity and finite element modelling. Residual bond strength for different levels of corrosion is obtained through different bond models available in the literature. A finite element model is also created for corroded RC beams with varying levels of corrosion. Residual flexural capacity obtained through the analytical approach and finite element approach is validated with the available experimental results. Finite element modelling can be used to forecast the remaining strength of corroded RC flexural elements since the results are in good agreement with experimental and analytical findings.*

Keywords *- Bond strength, Corrosion, Residual flexural capacity, Finite element modelling, Reinforced concrete element.*

1. Introduction

Steel reinforcement corrosion is a major cause of deterioration in RC structures, particularly flexural members and structures located in coastal/marine environments. Rebar's cross-sectional area is decreased as a result of corrosion, reduced mechanical properties of rebar (Wang & Liu, 2008) and changed bond strength between rebar and concrete. The severity of the damage depends on the types of corrosion, i.e., pitting or uniform, the extent of corrosion and the location of corrosion. Many experimental investigations are available in the literature assessing the flexural capacity of corroded beams for various corrosion levels. Al-Sulaimani et al. (1990) studied the failure of beams with and without bond strength failure. Rodriguez et al. (1997) did an experimental investigation of corroded RC beams using tensile, compressive and shear reinforcement with different levels of corrosion. Maaddawy et al. (2005) studied the behavior of corroded beams under sustained loading. Smith (2007) studied the failure pattern of corroded RC beams under sustained loading for a different level of corrosion. Sun et al. (2015) investigated the failure mode of corroded RC members under repeated loading. Recupero et al. (2018) investigated the effect of corrosion on flexural and shear reinforcement. Song et al. (2019) investigated the fatigue behavior of corroded RC beams. Yalciner et al. (2020) investigated the effect of corrosion on the flexural strength of RC beams.

The influence of corrosion on RC structures based on a numerical approach has also been reported in the pieces of literature; Wang et al., 2008 did a finite element investigation of corroded RC beams. Azad et al. (2010) predicted the residual flexural capacity of the beam analytically. Kallias et al. (2010), Guzman et al., 2012; Jnaid et al., 2016 predicted the response of corroded RC beams by finite element modelling. Abdelatif et al., 2018 studied the finite element response of corroded splice joints. Hawileh et al., 2019 studied the response of beams with externally bonded (EB) fiber-reinforced polymer (FRP) systems. Alabduljabbar et al., 2020 predicted the flexural model of a corroded RC beam. Meet et al., 2021 investigated the nonlinear response of corroded RC beams. Peng et al., 2022 predicted the flexural behavior of corroded beams using an adaptive neuro fuzzy inference system.

The major effect of corrosion which causes loss of ultimate capacity of flexural members, is the change in bond strength which increases initially for smaller levels of corrosion due to the formation of rust whose volume is higher than the volume of steel lost. Oncethe concrete is cracked up to the cover front, the bond strength starts decreasing. Several studies have been done on bond deterioration due to corrosion and its effect on the ultimate load-carrying capacity of corroded RC structures. Stanish et al., 1999; Wei-liang et al., 2001 studied the bond behavior of concrete under corrosion. Chung et al., 2004; Bhargava et al., 2007 provided the prediction model of bond strength for corroded bars. Wu & Hao, 2012; Shetty et al. (2016); Elghazy et al., 2018; Bani et al. (2019) also studied the bond strength of concrete for corroded reinforcement. The researchers have also reported that the presence of stirrups in the vicinity of flexural steel positively affects the residual bond strength. Also, laboratory experiments revealed that flexural members extensively attacked by corrosion failed in shear instead of ductile failure (Wang et al., 2008).

Since the experimental testing of corroded RC elements in the lab is a cumbersome task as the development and simulation of different corrosion levels in the reinforcement steel bars may not be accurate enough and also to make an assessment of the residual flexural capacity of the corroded RC elements through experimental investigations are expensive and time-consuming approach. Hence, there is a need to develop a more convincing and economical analytical approach to predict the residual load-carrying capacity of corroded RC elements. So that the cost of experimental testing, inspection, repair work and maintenance of the corrosion-affected RC structures gets minimized. If accurate modelling of corroded structures and deterioration of material properties is done, then corroded structures' safety and service life can be predicted accurately.

In this present study, the residual flexural capacity of corroded RC elements is estimated by using an analytical method (Wang & Liu, 2008) and a nonlinear finite element modelling technique through finite element analysis (FEA) based ATENA software. Here different bond models available in the literature have been used for predicting the affected residual bond strength of corroded RC flexural members. Results obtained through FEM modelling and analytical study are validated with the available experimental data (Rodriguez et al., 1997; Smith, 2007).

2. Analytical Calculation of Residual Flexural Capacity of RC Beam

The method suggested by Wang & Liu (2008) has been used to calculate the residual flexural capacity of corroded RC beams. The cross-sectional area of steel, modulus of elasticity and steel yield strength is calculated as Wang & Liu (2008) suggested. Affected bond strength has been calculated as suggested by different authors (Bhargava et al., 2007; Stanish et al., 1999; Chung et al., 2004; Wang et al., 2008). Residual flexural capacity has been calculated for the beams whose experimental data are already available in the literature (Rodriguez et al., 1997; Smith, 2007).

3. Finite Element Modelling

Corroded beam has been modelled in FEA-based ATENA software to evaluate the flexural capacity of corroded beams. Affected parameters such as yield strength, modulus of elasticity, the cross-sectional area of reinforcement and bond strength are used as input in order to simulate the corroded RC beam. Four-point loading is used in ATENA to simulate the experimental load application.

3.1. Concrete Modelling

Modelling of concrete in ATENA 2D is done by selecting SBETA material which is one of the available material types in the ATENA material library, as shown in Fig.1. After selecting SBETA material, uniaxial compressive strength of the concrete is given as shown in Fig. 2. Rest of the parameters required for nonlinear analysis is calculated by the default formula of ATENA, like stress-strain curve of concrete as shown in Fig. 3. If experimental values of parameters are available then the available value should be used.

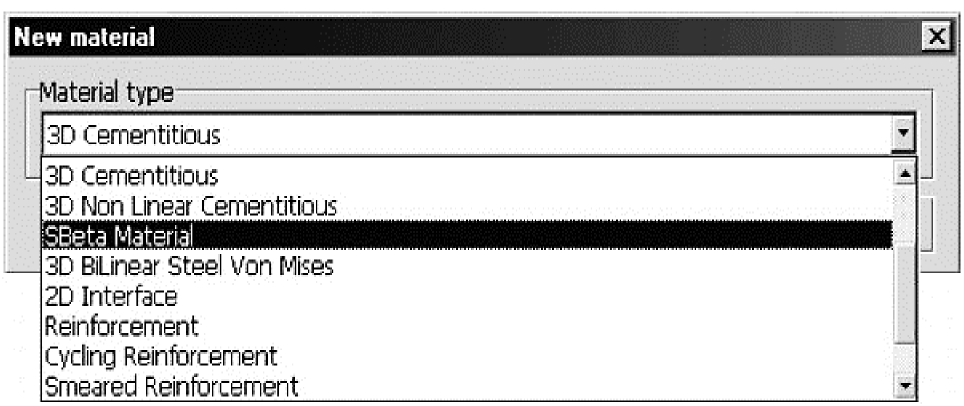

Fig. 1 Selection of material in ATENA

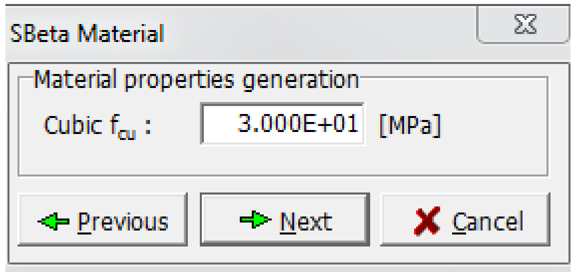

Fig. 2 Assigning compressive strength of concrete

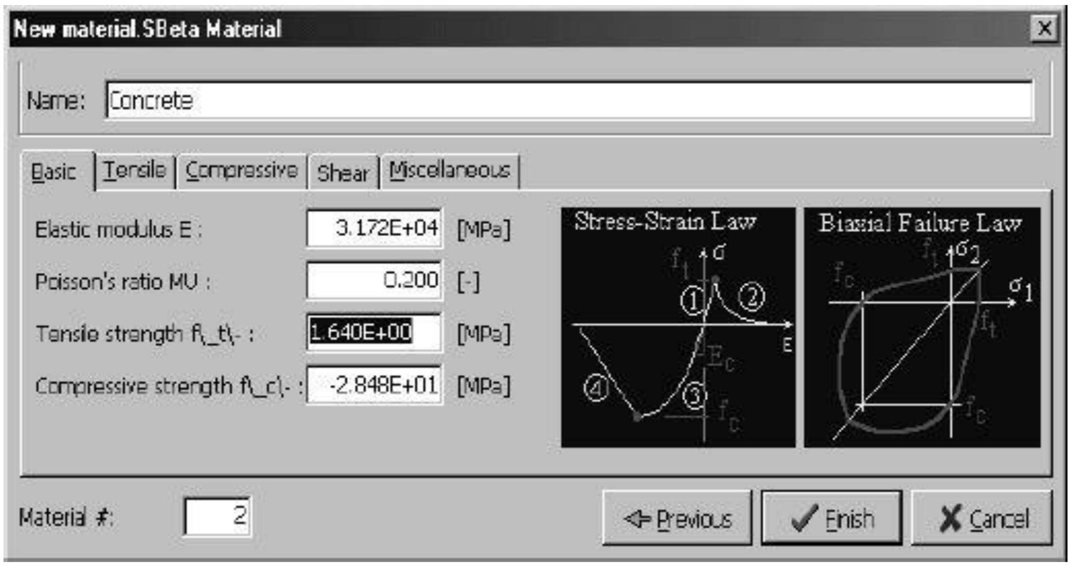

Fig. 3 Auto-generated stress-strain curve of concrete

3.2. Mechanical Properties of Reinforcement

Since corrosion reduces the value of yield strength and elastic modulus of reinforcements, reduced values should be used while modelling. Reduced yield strength of reinforcement is given by the following relationship:

$$f_{yx} = (1 - \frac{1.24\Delta w}{100}) f_y$$

f_{yx}= Reduced value of yield strength
f_y= yield strength of rebar
Δw = percentage loss of mass (%) of rebar

Reduced modulus of elasticity of reinforcement is given by following the relationship

$$E_{sx} = (1 - \frac{0.75\Delta w}{100}) E_s$$

E_{sx} = Reduced value of elastic modulus of rebar
E_s = Initial value of elastic modulus
Δw = percentage loss of mass (%) of rebar
Fig. 4 shows the assignment of yield strength and elastic modulus for rebar modelling.

3.3. Cross-sectional Area of Reinforcement

Reinforcement is modelled by giving the coordinate of starting and end point of reinforcement as well as the diameter and number of bars (Fig.5 and Fig. 6). As finite elements of any particular size and type are generated, ATENA changes the reinforcements into truss elements. Hence reinforcements are used as truss elements for finite element analysis.

To calculate the reduced area, attack penetration depth x to be determined as mentioned earlier.

$$x = \frac{d\Delta w}{400}$$

Where x = attack penetration depth,
d= diameter of rebar,
Δw = loss of weight of rebar (%).

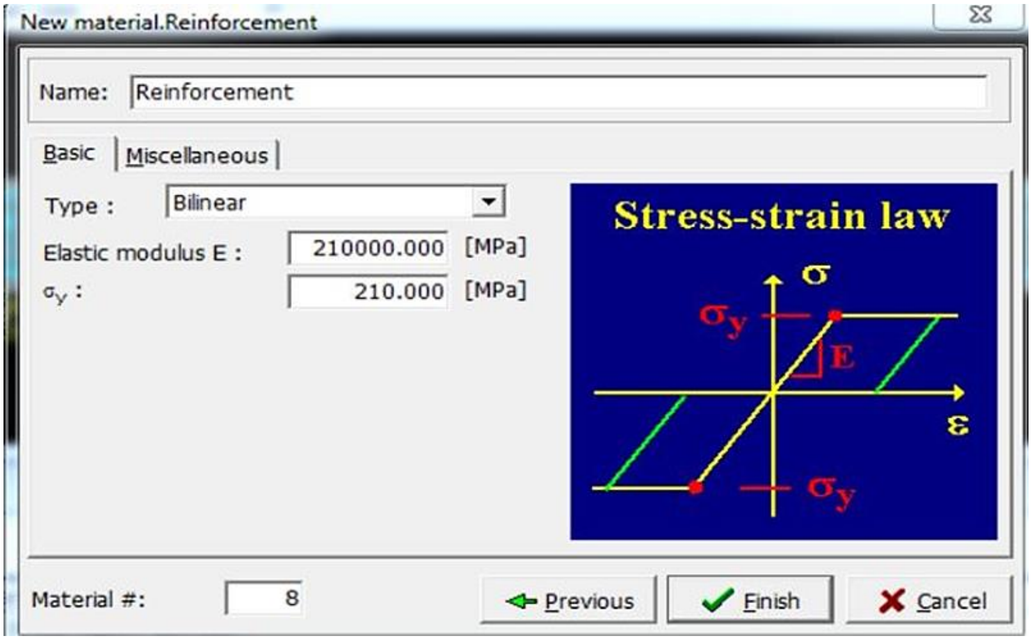

Fig. 4 Assignment of mechanical property of corroded rebar

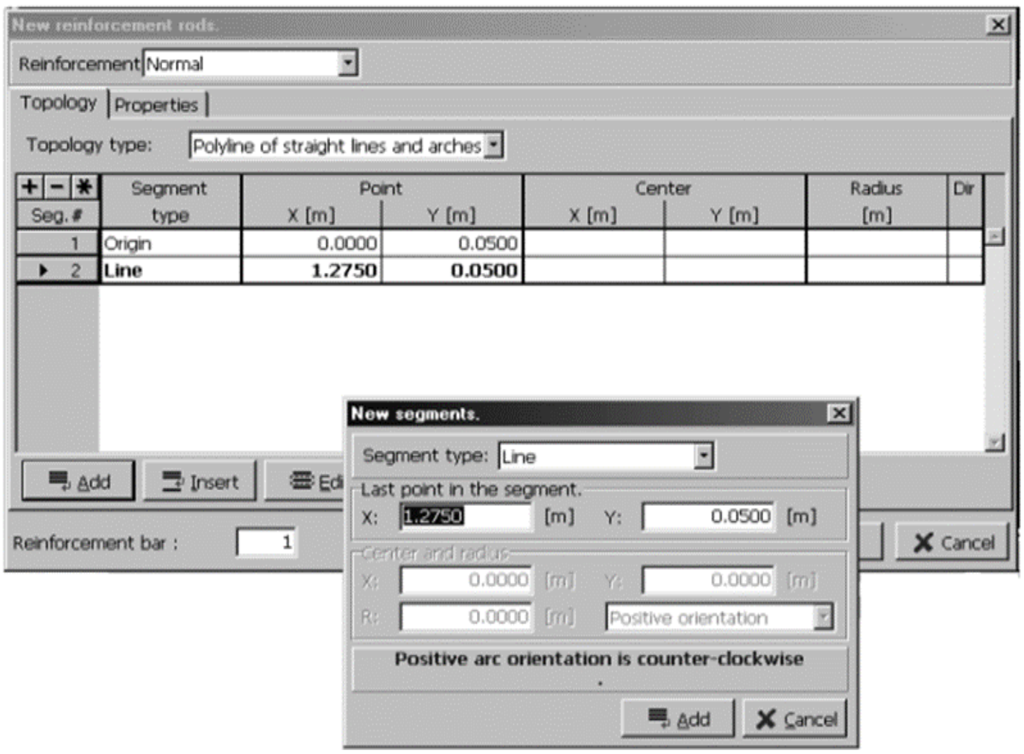

Fig. 5 Assignment of rebar end

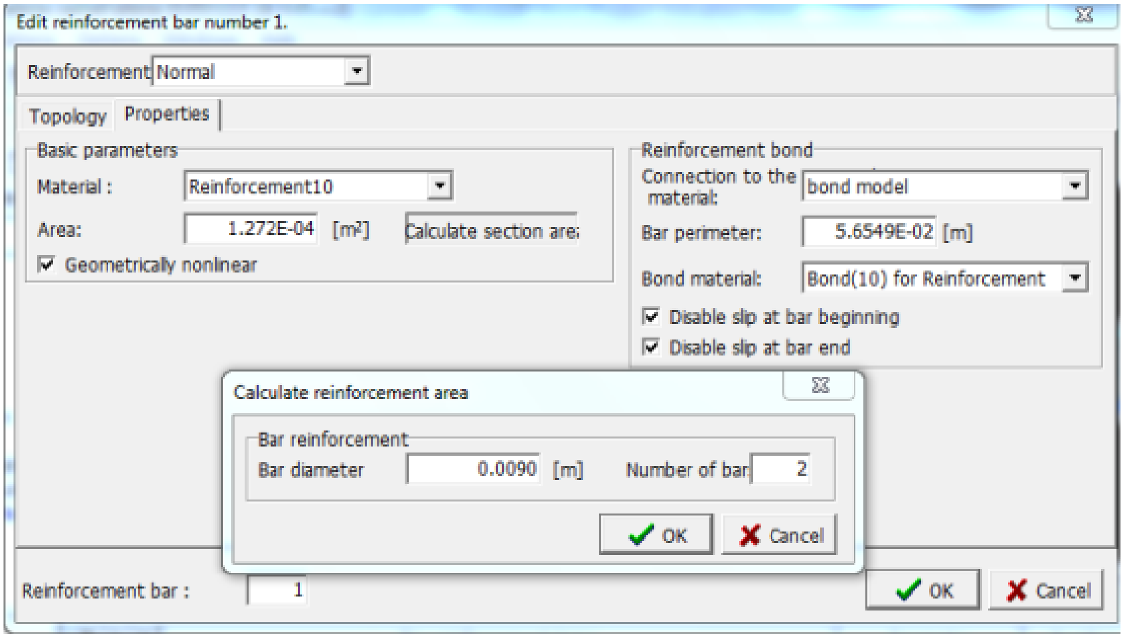

Fig. 6 Assignment of number and area of rebar

3.4. Bond Strength between Concrete and Reinforcement

Bond strength is to be modelled by using the user-defined bond model. To obtain a user-defined bond model CEB FIP bond model (Fig. 7) is to be used. The relations used to obtain the CEB FIP bond model are shown below. Table 1 shows the different parameters used to obtain the bond stress-slip curve. To obtain the residual bond strength of the corroded bar bond model of Wang & Liu (2008) is used here.

$$\tau_b = \tau_{max}\left(\frac{s}{s_1}\right)^{\alpha}, 0 \le s \le s_1$$

$$\tau_b = \tau_{max} \qquad s_1 \le s \le s_2$$

$$\tau_b = \tau_{max} - (\tau_{max} - \tau_f)\left(\frac{s - s_2}{s_3 - s_2}\right), s_2 \le s \le s_3$$

$$\tau_b = \tau_f, \qquad s \le s_3$$

Where τ_b= available bond strength
s = slip
s_1, s_2, s_3 can be obtained from Table 1.

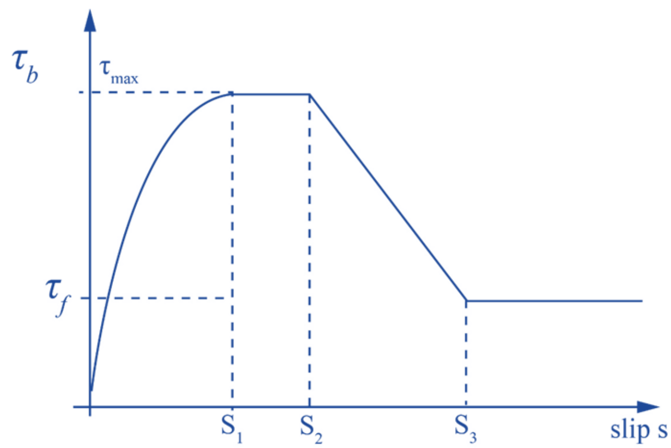

Fig. 7 Bond strength - slip law by CEB-FIP code (Cervenka et al., 2012)

To obtain the user-defined bond model, the changed ultimate bond strength τ_{max} has to be used.

Table 1. Parameters to be used for bond strength-slip relationship (CEB-FIP code)

Value	**Unconfined concrete**		**Confined concrete**	
	Bond conditions		**Bond conditions**	
	Good	All other cases	Good	All other cases
S1	0.6 mm	0.6 mm	1.0 mm	
S2	0.6 mm	0.6 mm	3.0 mm	
S3	1.0 mm	2.5 mm	Clear rib spacing	
α	0.4		0.4	
τ_{max}	$2.0\sqrt{f_c}$	$1.0\sqrt{f_c}$	$2.5\sqrt{f_c}$	$1.25\sqrt{f_c}$
τ_b	$0.15\ \tau_{max}$		$0.40\ \tau_{max}$	

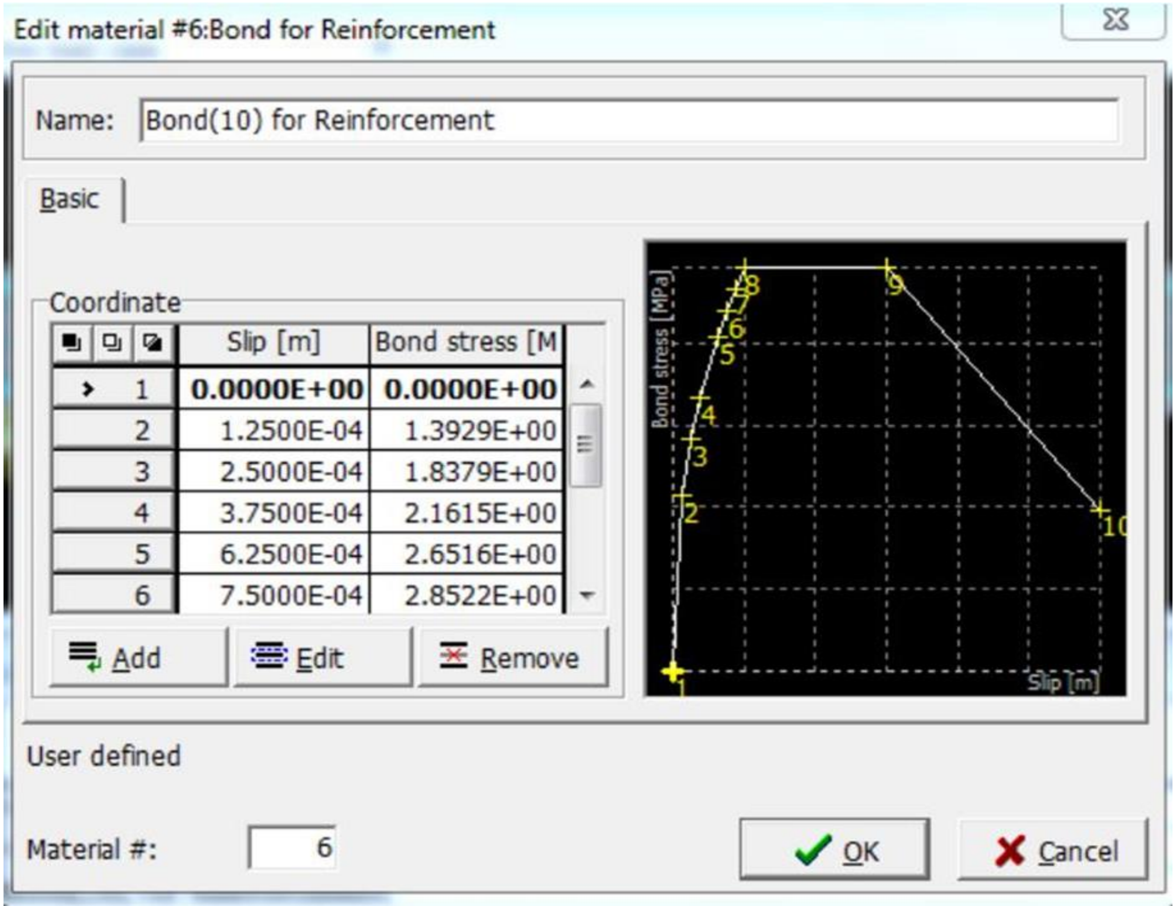

Fig. 8 Bond stress vs slip curve

For the different levels of corrosion, if the maximum bond strength at any particular corrosion level is greater than the maximum bond strength for zero-level corrosion, then a perfect bond model will be used. Clear rib spacing is taken as 0.6 times the diameter of the uncorroded bar. The bond stress vs slip value used in ATENA is shown in Fig. 8.

4. Validation of Experimental data

Experimental data obtained through pieces of literature are used for modelling in ATENA. All the affected parameters are modelled as described in the above sections to simulate the actual condition of corroded flexural members. Finite element analysis is done to validate with experimental available residual flexural capacity and results obtained by the methodology suggested by Wang & Liu (2008) for calculation of residual flexural capacity as described earlier. Experimental data used for validation are taken from the experimental study of Rodriguez et al. (1997) and Smith's experiment (2007). Fig. 9 shows the detailed dimension of the RC beam used by Rodriguez et al. (1997). Fig.10 and Fig.11 show the FE model of the beams used by Rodriguez et al. (1997) and Smith's experiment (2007).

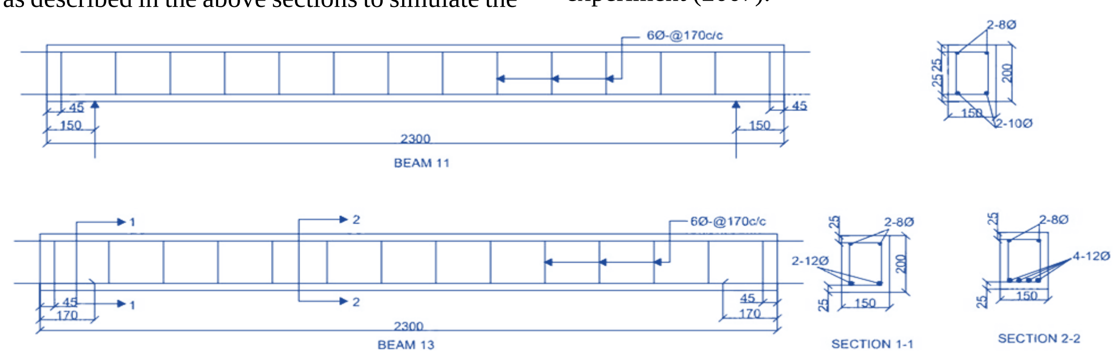

Fig. 9 RC beam used by Rodriguez et al (1997)

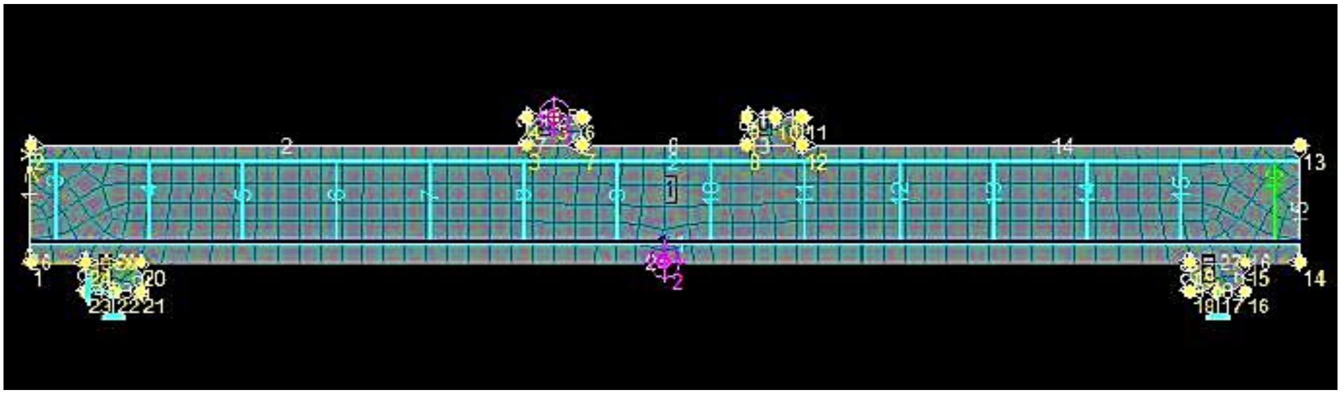

Fig. 10 FE model of RC beam used by Rodriguez et al. (1997)

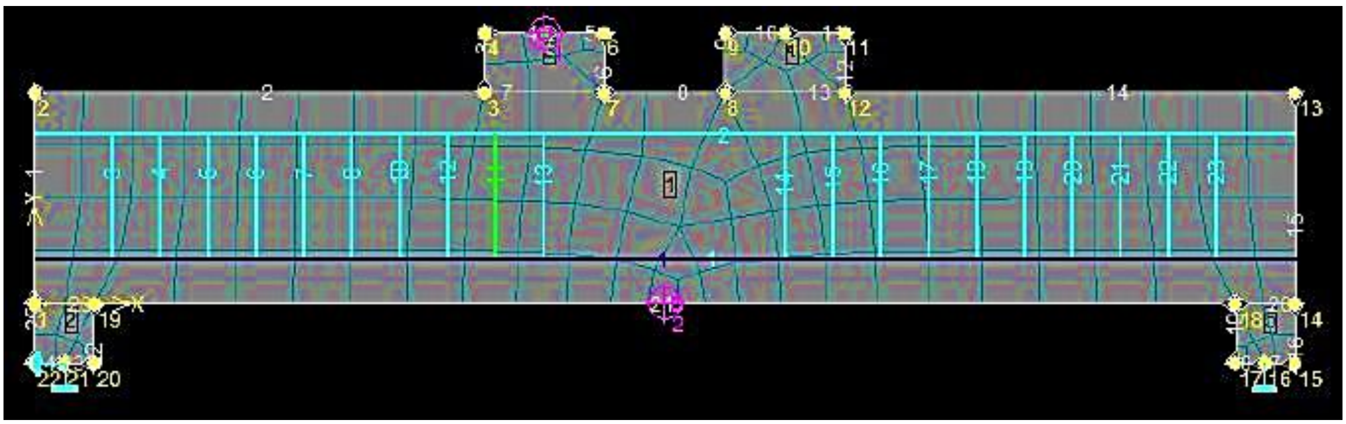

Fig. 11 FE model of RC beam used in Smith's experiment (2007)

5. Results and Discussion

Residual moment capacity (by analytical approach, table 2) obtained using the bond model of Wang & Liu (2008) is close to experimental results; hence this bond model is used here for Finite element modelling. Types of element used for FE modelling is quadriletral type. Force has been applied by displacement control method with 0.0002mm / Load step. The element size used for the modelling beam used by Rodriguez et al. (2007) is taken as 0.038mm, and that for the beam used in Smith's experiment (2007) as 0.044mm. Load deflection curve obtained by finite element analysis and shown in Fig. 12 and Fig. 13 for beam 112 (Rodriguez et al., 2007) and 311 (Smith's experiment, 2007), respectively.

Similarly, load-deflection curves for other beams for a different level of corrosion are obtained, and the ultimate load for each strength used to calculate the residual flexural capacity is calculated using the different bond models. Then residual flexural capacity is calculated, as mentioned earlier (Wang & Liu, 2008). Results obtained through FE modelling have been compared with experimental results and analytical results.

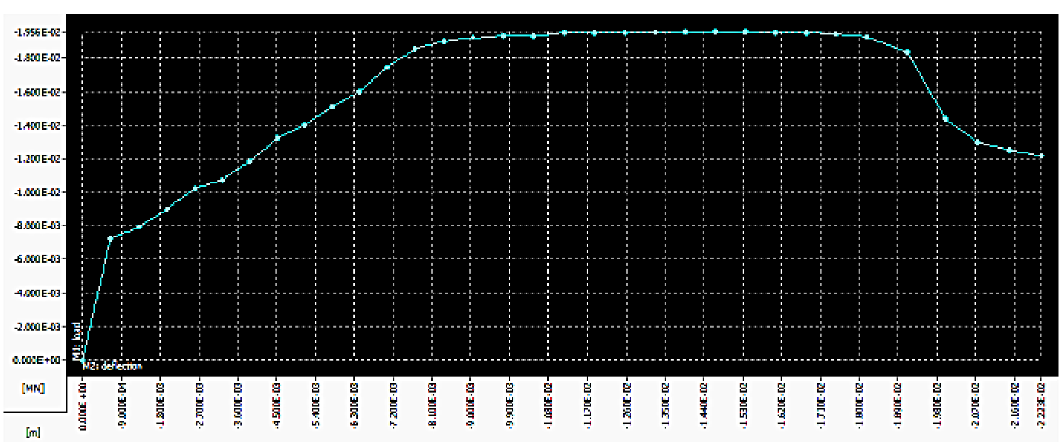

Fig. 12 Load deflection curve for beam 112 (Rodriguez et al., 1997)

Table 2. Comparison of residual moment capacity (in kN-m) obtained by differentbond models, ATENA and experiment (Rodriguez et al., 1997)

The residual flexural capacity of corroded beam obtained by analytical method (Wang & Liu, 2008) for different bond model						ATENA	EXP.
Beam no	Chung et al bond model (2004)	Bhargava et al. pullout bond model (2007)	Bhargava et al. flexural bond model (2007)	Stanish et al. bond model (1999)	Wang and Liu (2008)		
112	14.52	14.52	14.52	14.52	14.52	15.65	15.70
113	5.03	6.71	1.60	8.08	8.07	9.89	10.10
114	5.55	8.13	2.21	8.44	8.43	10.42	10.50
115	7.11	9.30	4.54	9.24	9.24	11.42	11.60
116	3.23	2.32	0.27	0.18	6.24	8.01	8.60
122	37.55	37.55	37.55	37.55	37.55	40.54	38.30
123	19.12	27.22	16.51	27.06	26.06	27.75	27.20
124	16.11	25.65	11.26	25.34	21.17	24.02	20.40
125	16.57	26.13	12.06	25.96	20.43	24.63	22.90
126	21.03	27.90	20.22	27.73	27.09	28.38	29.00
131	37.84	37.84	37.84	37.84	37.84	38.60	36.60
133	18	27.42	15.7	27.24	24.63	30.68	25.20
134	19.80	28.03	19.0	27.86	26.54	29.6	25.30
135	15.94	26.22	12	25.91	18.97	22.30	24.70
136	15.55	26.25	11.28	26.08	19.55	24.00	21.20
211	37.36	37.36	37.36	37.36	37.36	34.34	38.40
213	15.24	25.51	9.76	25.27	19.76	25.62	19.40
214	12.03	17.96	5.16	23.36	14.45	21.31	20.90
215	18.10	27.02	14.64	26.80	26.32	28.67	28.20
216	21.76	27.98	20.98	27.76	26.18	29.12	26.40
311	38.40	38.40	38.40	38.40	38.40	36.30	38.1
313	25.40	29.35	25.9	29.21	29.31	32.17	28.20
314	15.04	24.40	7.88	24.86	24.94	29.80	28.50
315	14	21.64	6.44	24.14	24.25	27.72	20.20
316	17.40	26.17	11.65	25.98	26.12	29.88	27.50

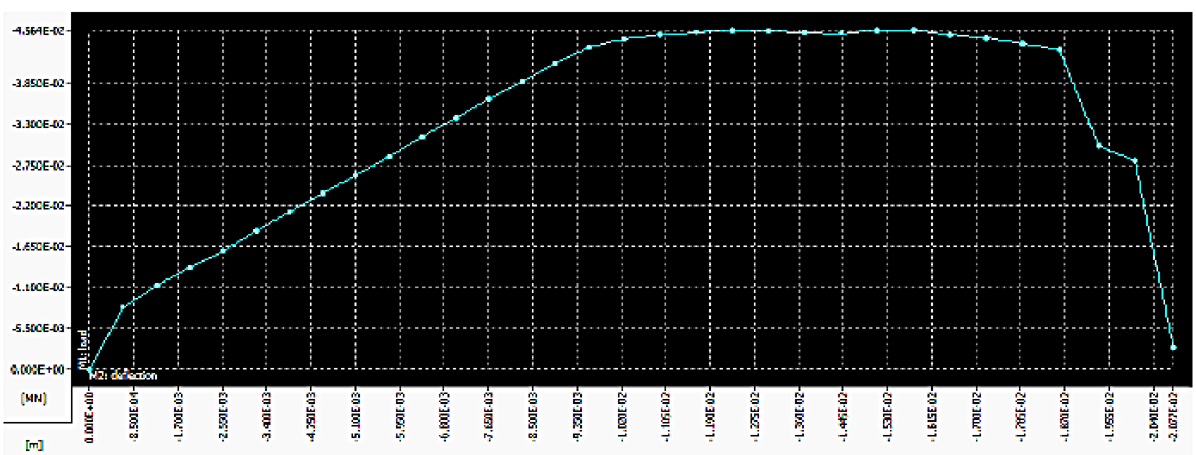

Fig. 13 Load deflection curve for beam 311 (Smith's experiment, 2007)

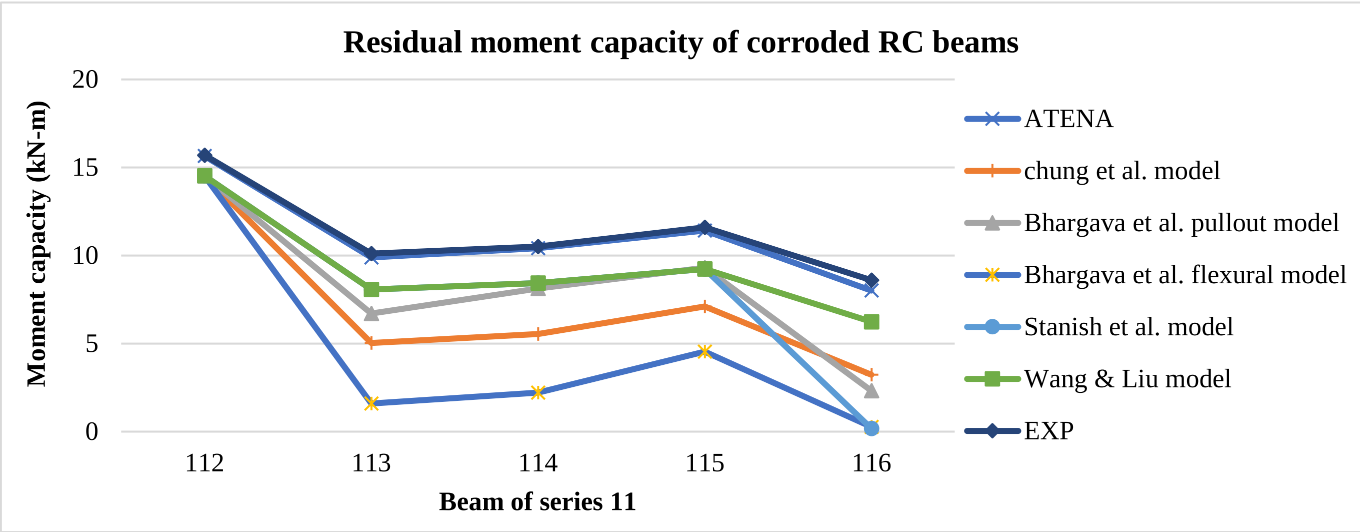

Fig. 14 Comparison with flexural capacity for beam series 11

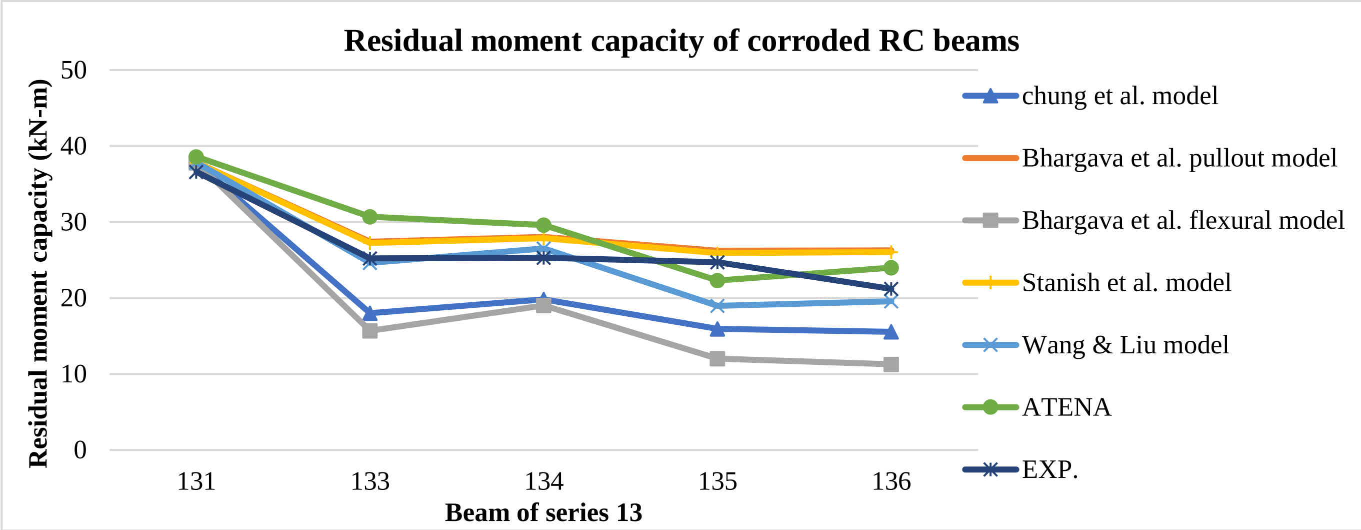

Fig. 15 Comparison with flexural capacity for beam series 13

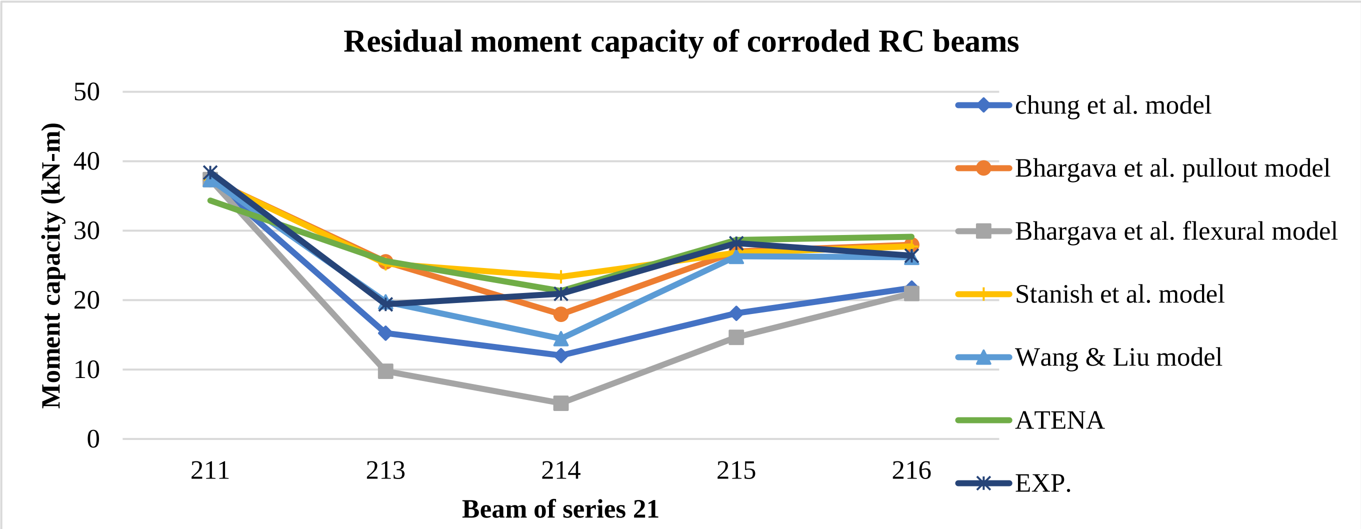

Fig. 16 Comparison with flexural capacity for beam series 21

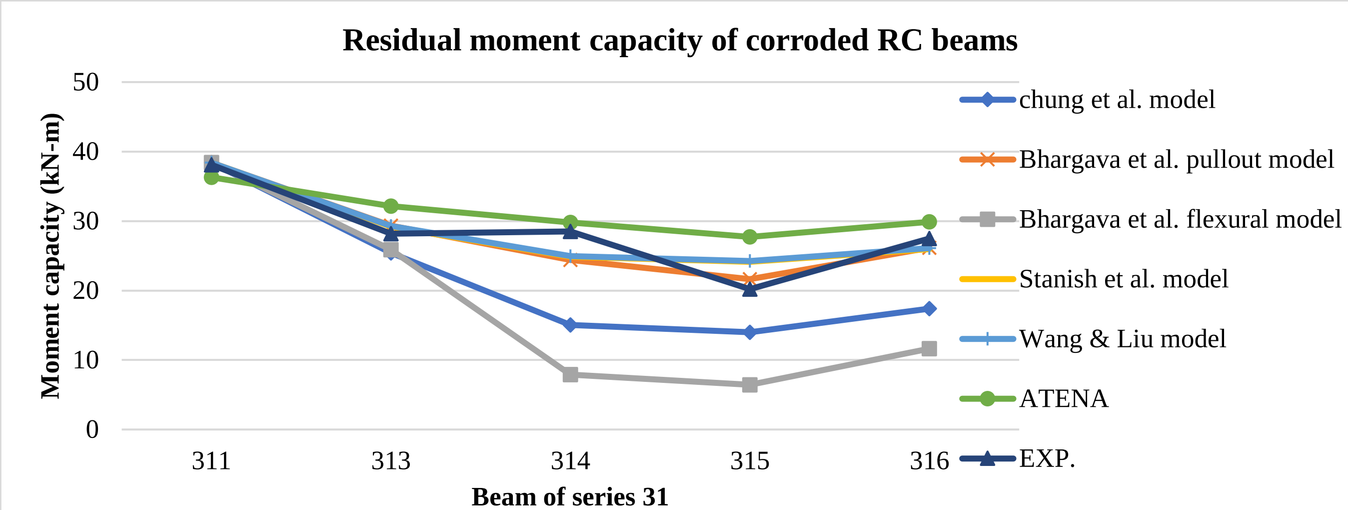

Fig. 17 Comparison with flexural capacity for beam series 31

Suppose the residual flexural capacity obtained by different bond models using an analytical approach is compared. In that case, it is clear that the bond model suggested by Chung et al. (2004) and the flexural model of Bhargava et al. (2007) underestimate the residual flexural capacity. Bond models of Stanish et al. (1999) and the pullout modelof Bhargava et al. (2007) predict better results than the bond model suggested by Chung et al. (2004) and the flexural model of Bhargava et al. (2007). However, flexural capacity is underestimated for the beam with a higher corrosion level (beam 116). This is because these entire bond models, except Wang and Liu's model (2008), do not consider the contribution of shear reinforcement, which contributes mainly to bond strength at higher levels of corrosion. Wang and Liu's (2008) model considers the contribution of stirrups predicting good results. For beam 214 Wang andLiu model underestimates the capacity, but if we see the experimental data of beams 213 and 214, we expect the flexural capacity for beam 214 to decrease. It can be said that Wang and Liu's model (2008) is the best in comparing all models' results. As a result, for bond strength modelling, the Wang and Liu model (2008) is used for finite element modelling, and the results agree well with the experimental results.

As obtained in the experiment of Rodriguez et al. (1997), If residual flexural capacity is calculated for the beam used in Smith's experiment (2007) by analytical approach, we cansay that the bond models of Chung et al. (2004) and the flexural model of Bhargava et al. (2007) still underestimatethe results. The pullout bond model of Bhargava et al. (2007) and the bond model of Stanish et al. (1999) predict somewhat better. However, due to not taking the contribution of stirrups, they also predict a lowervalue at a higher level of corrosion. The Wang and Liu model (2008) results predict results closer to the experimental results. If moment capacity at zero level corrosion and 11.56 % corrosion is compared, then the loss of moment capacity is not much. This is due to the fact that stirrups are provided at a closer spacing which does not allow the bond strength to decrease much more. Hence Wang and Liu's model (2008) is used for modelling bond strength in ATENA for 2D modelling, and results obtained by finite element modelling in ATENA are in good agreement with experimental results.

Table 3. Comparison of residual load carrying capacity (kN) obtained by differentbond models, ATENA and experiment (Smith's experiment,2007)

The residual flexural capacity of corroded beam obtained by analytical method (Wang & Liu, 2008) for different bond model						ATENA	EXP.
Beam no	**Chung et al bond model (2004)**	**Bhargava et al. pullout bond model (2007)**	**Bhargava et al. flexural bond model (2007)**	**Stanish et al. bond model (1999)**	**Wang and Liu (2008)**		
BS 01	116.10	116.10	116.10	116.10	116.10	116.10	140.96
BS 08	114.1	114.1	114.1	114.1	114.1	115.10	117.40
BS 07	110.35	110.6	110.3	111	110.65	112.02	115.86
BS 10	79.35	104.75	101.3	105	104.3	105.44	100.81
BS 09	57.25	100.8	70.75	100.75	100.35	104.76	101.27
BS 12	39.25	75.85	39.2	93.2	93.8	93.02	96.47
BS 11	34.5	65.55	30.3	86.75	91.1	90.88	96.08

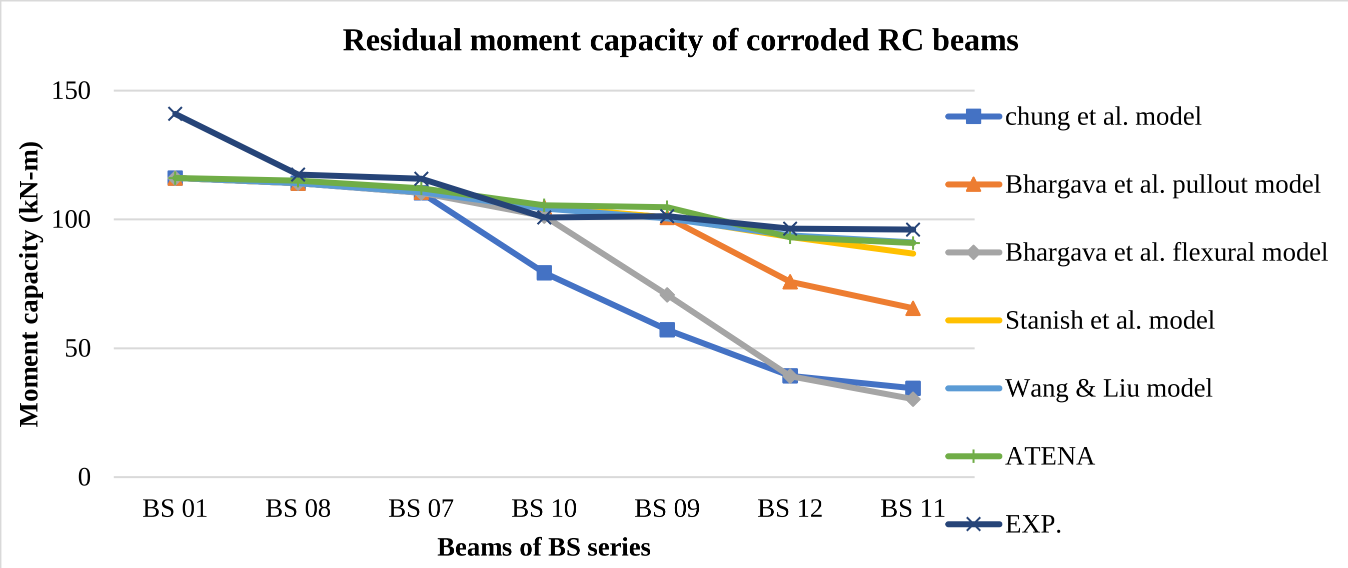

Fig. 18 Comparison with flexural capacity for beam series of BS

6. Conclusion

Using FE analysis and analytical approach, different bond models are used to obtain corroded members' bond strength and residual flexural capacity. Results show that corrosion strongly affects flexural members' bond strength and flexural capacity. Finite element analysis is also performed for corroded members.

Based on the above study following conclusions are drawn:

- Bond strength at higher corrosion levels is mainly due to the confinement force provided by the stirrups. Therefore, at a higher level of corrosion importance of stirrups is increased.
- The residual bond strength between corroded reinforcement and concrete depends on corrosion pressure, friction coefficient, and confinement provided to the corroded reinforcement by cracked concrete and stirrups.
- The available bond strength between concrete and corroded reinforcement can be used to determine the residual flexural strength of corroded RC flexural members.
- Residual flexural capacity by Wang and Liu model (2008) gives good agreement with analytical results, experimental results and results obtained in ATENA. As a result, this model can predict the residual flexural capacity of corroded flexural members.

References

[1] Amged O. Abdelatif, Joško Ožbolt, and Serena Gambarelli, "3D Finite Element Modelling of Corrosion of Lap Splice Joints in Concrete," *Construction and Building Materials*, vol. 169, pp. 124-131, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[2] Hisham Alabduljabbar et al., "Prediction of the Flexural Behavior of Corroded Concrete Beams Using Combined Method," *Structures*, vol. 25, pp. 1000-1008, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[3] G. J. Al-Sulaimani et al., "Influence of Corrosion and Cracking on Bond Behavior and Strength of Reinforced Concrete Members," *Structural Journal*, vol. 87, no. 2, pp. 220-231, 1990. [CrossRef] [Google Scholar] [Publisher Link]

[4] Azad, A. K., S. Ahmad, and B. H. A. Al-Gohi, "Flexural Strength of Corroded Reinforced Concrete Beams," *Magazine of Concrete Research*, vol. 62, no. 6, pp. 405-414, 2010. [CrossRef] [Google Scholar] [Publisher Link]

[5] E. BaniAsad, and M. Dehestani, "Incorporation of Corrosion and Bond-Slip Effects in Properties of Reinforcing Element Embedded in Concrete Beams," *Structures*, vol. 20, pp. 105-115, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[6] Kapilesh Bhargava et al., "Corrosion-Induced Bond Strength Degradation in Reinforced Concrete—Analytical and Empirical Models," *Nuclear Engineering and Design*, vol. 237, no. 11, pp. 1140-1157, 2007. [CrossRef] [Google Scholar] [Publisher Link]

[7] Cervenka, V., L. Jendele, and J. Cervenka. "ATENA Program Documentation-Theory," *Cervenka Consulting Ltd., Prague, Czech Republic*, 2012

[8] Lan Chung et al., "Correction Factor Suggestion for ACI Development Length Provisions Based on Flexural Testing of RC Slabs With Various Levels of Corroded Reinforcing Bars," *Engineering Structures,* vol. 26, no. 8, pp. 1013-1026, 2004. [CrossRef] [Google Scholar] [Publisher Link]

[9] Tamer El Maaddawy, Khaled Soudki, and Timothy Topper, "Long-Term Performance of Corrosion-Damaged Reinforced Concrete Beams," *ACI Structural Journal*, vol. 102, no. 5, p. 649, 2005. [CrossRef] [Google Scholar] [Publisher Link]

[10] Mohammed Elghazy et al., "Experimental Results and Modelling of Corrosion-Damaged Concrete Beams Strengthened with Externally-Bonded Composites," *Engineering Structures*, vol. 172, pp. 172-186, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[11] Santiago Guzmán, Jaime C. Gálvez, and José M. Sancho, "Modelling of Corrosion-Induced Cover Cracking in Reinforced Concrete by an Embedded Cohesive Crack Finite Element," *Engineering Fracture Mechanics*, vol. 93, pp. 92-107, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[12] R.A. Hawileh et al., "Finite Element Modeling of Reinforced Concrete Beams Externally Strengthened in Flexure with Side-Bonded FRP Laminates," *Composites Part B: Engineering*, vol. 173, pp. 92-107, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[13] J Fares Jnaid, and Riyad S. Aboutaha, "Residual Flexural Strength of Corroded Reinforced Concrete Beams," *Engineering Structures*, vol. 119, pp. 198-216, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[14] Alexandros N. Kallias, and M. Imran Rafiq, "Finite Element Investigation of the Structural Response of Corroded RC Beams," *Engineering Structures*, vol. 32, no. 9, pp. 2984-2994, 2010. [CrossRef] [Google Scholar] [Publisher Link]

[15] Sompura Meet, Choudhury Trishna, and Kwatra Naveen, "Investigating the Nonlinear Performance of Corroded Reinforced Concrete Beams," *Journal of Building Engineering*, vol. 44, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[16] Niels Saabye Ottosen, "A Failure Criterion for Concrete," *Journal of the Engineering Mechanics Division*, vol. 103, no. 4, pp. 527-535, 1977. [CrossRef] [Google Scholar] [Publisher Link]

[17] Jun Peng et al., "Prediction and Optimization of the Flexural Behavior of Corroded Concrete Beams Using Adaptive Neuro Fuzzy Inference System," *Structures*, vol. 43, pp. 200-208, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[18] Antonino Recupero, Nino Spinella, and Francesco Tondolo, "Failure Analysis of Corroded RC Beams Subjected to Shear-Flexural Actions," *Engineering Failure Analysis*, vol. 93, pp. 26-37, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[19] Dr J Rodriguez, LM Ortega, and J Casal, "Load Carrying Capacity of Concrete Structures with Corroded Reinforcement," *Construction and Building Materials*, vol. 11, no. 4, pp. 239-248, 1997. [CrossRef] [Google Scholar] [Publisher Link]

[20] Akshatha Shetty, Katta Venkataramana, and K. S. Babu Narayan, "Experimental and Numerical Investigation on Flexural Bond Strength Behavior of Corroded NBS RC Beam," *International Journal of Advanced Structural Engineering (IJASE)*, vol. 7, no. 3, pp. 223-231, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[21] Smith, R. "*The Effects of Corrosion on the Performance of Reinforced Concrete Beams*," Masc Thesis, Ryerson University, Toronto, 2007. [Google Scholar]

[22] Li Song, Zhiwei Fan, and Jian Hou, "Experimental and Analytical Investigation of the Fatigue Flexural Behavior of Corroded Reinforced Concrete Beams," *International Journal of Concrete Structures and Materials*, vol. 13, no. 1, pp. 1-14, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[23] Alaa M. Morsy, Nabil H. El-Ashkar, and T. M. Elrakib, "Methods for Reducing Concrete Cover De-Bonding in R.C. Beams Strengthened in Flexure with CFRP Strips," *SSRG International Journal of Civil Engineering*, vol. 4, no. 11, pp. 8-13, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[24] Stanish, Kyle David, "*Corrosion Effects on Bond Strength in Reinforced Concrete*," Phd Thesis, 1999. [Google Scholar]

[25] Junzu Sun, Qiao Huang, and Yuan Ren, "Performance Deterioration of Corroded RC Beams and Reinforcing Bars under Repeated Loading," *Construction and Building Materials*, vol. 96, pp. 404-415, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[26] X. H. Wang, and X. L. Liu, "Modelling Effects of Corrosion on Cover Cracking and Bond in Reinforced Concrete," *Magazine of Concrete Research*, vol. 56, no. 4, pp. 191-199, 2004. [CrossRef] [Google Scholar] [Publisher Link]

[27] Xiaohui Wang, and Xila Liu, "Bond Strength Modeling for Corroded Reinforcements," *Construction and Building Materials*, vol. 20, no. 3, pp. 177-186, 2006. [CrossRef] [Google Scholar] [Publisher Link]

[28] Xiaohui Wang, and Xila Liu, "Modeling Bond Strength of Corroded Reinforcement without Stirrups," *Cement and Concrete Research*, vol. 34, no. 8, pp. 1331-1339, 2004. [CrossRef] [Google Scholar] [Publisher Link]

[29] Wang, Xiao-Hui, and Xi-La Liu. "Modeling the Flexural Carrying Capacity of Corroded RC Beam," *Journal of Shanghai Jiaotong University (Science)*, vol. 13, no. 2, pp. 129-135, 2008. [CrossRef] [Google Scholar] [Publisher Link]

[30] Jin Wei-liang, and Zhao Yu-xi, "Effect of Corrosion on Bond Behavior and Bending Strength of Reinforced Concrete Beams," *Journal of Zhejiang University-Science A*, vol. 2, no. 3, pp. 298-308, 2001. [CrossRef] [Google Scholar] [Publisher Link]

[31] Wu, Hao, "*Bond Degradation and Residual Flexural Capacity of Corroded RC Beams*," Masc Thesis, Ryerson University, Toronto, 2012. [Google Scholar]

[32] H. Yalciner et al., "Flexural Strength of Corroded Reinforced Concrete Beams," *ACI Structural Journal*, vol. 117, no. 1, pp. 29-41, 2020. [CrossRef] [Google Scholar] [Publisher Link]