Nonlinear Finite Element Method Analysis of After Fire Reinforced Concrete Beam Strengthened with Carbon Fiber Strip

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Abstract. Concrete which is exposed to high temperature will experience strength degradation. This research obtained nonlinear Finite Element numerical model for Reinforced Concrete (RC) Beam after-fire and then strengthened with Carbon Fiber Strip on the flexural area. RC beam before the fire (NB), after fire (AFB) and strengthened after (CAFB) FEM model were compared with the actual experimental results. Using ATENA v.2.1.10 and GID as Pre-Processor, the crack patterns of the numerical model showed a good agreement with experimental results. Loading and displacement relationship also showed the same behavior. Stress and strain relationship of each RC beam also has been observed for each loading step. S-Beta element utilized on ATENA v.2.1.10 gave the excellent results on nonlinearity material behavior, especially for model NB and AFB. The value of stiffness obtained for AFB and CAFB in the experiment was higher than the sample from the numeric result namely 64% and 45%, while the ductility value obtained from the experiment was also smaller about 41%, and 17% in comparison to its numerical.

1. Introduction

Temperature load cause change in the physical and mechanical behavior of concrete that affects structural element characteristic in case of durability, stability, stiffness and strength degradation. In order to keep the function of structural element subjected to severe temperature load, strengthening is needed to be applied, for example, strengthening using Carbon Fiber Strip (CFS) as external reinforcement. Many researchers have conducted investigation both experimentally and numerically using CFRP for beam [1,2,3,4,5,6]: Malek (1991), Arduini (1997), Elhsani (1997), Pahala (2000), Ngudiyono (2001) and Chen (2005).

This research conducted a numerical model of reinforced concrete beam strengthened by CFS as an external reinforcement which is attached at the flexural area of the beam. A numerical model was developed by using non-linear Finite Element of software ATENA V.2.1.10 and GID as Pre-Processor. Validation of the model compared with the experimental results of Ngudiyono (2001) [3].

The numerical model resulted in this research showed the crack patterns and cracked propagation as the increasing of the load increments. In another part, the behavior of the model also observed in term of the load-displacement curve of reinforced concrete before the fire, reinforced concrete after fire and...
reinforced concrete after fire strengthened with CFS. Comparison study for the stiffness and ductility of the models have also been conducted.

Since the experimental research usually is time-consuming and demand a considerable amount of resources, numerical model analysis becomes an alternative method to observe structural behavior after some loading condition. In order to achieve a model that close to a real characteristic of the element, the numerical model in this research were developed based on the experimental investigation which is also used for validation. This research modeled the element by using non-linear material model provided as constitutive SBETA material (CCSbetaMaterial) while assumed the geometry as linear guidelines.

2. Theoretical Background

A constitutive model for a concrete material in ATENA uses smeared crack concept and fracture mechanic. Internal stress based on uniaxial stress-strain law. This law explains about concrete failure due to monotonic loading as shown in Figure 1. Maximum stress at uniaxial behavior \( f_{\text{eff}} \) determined based on biaxial failure surface as shown in Figure 2 from Kupfer et al. experimental (1969) [7].

![Figure 1. Stress-Strain Law for Concrete](source)

![Figure 2. Concrete Biaxial Failure Function.](source)

The multilinear stress-strain relationship is used for reinforcement on this model and the Carbon Fiber Strip model is based on Von Mises plasticity theory as shown in Figure 5 and 6.

![Figure 3. Fixed Crack Model](source)

![Figure 4. Rotated Crack Model](source)

![Figure 5. Multilinear Stress-Strain Law for Reinforcement.](source)

![Figure 6. Von Mises Yield Criteria](source)
The principal flexural crack behavior for Reinforced Concrete Element

Reinforced concrete beam, due to earlier tension crack of concrete material experiences crack at early loading stage as well. This characteristic is explained by Park and T. Pauley [10] as described in Fig 7.

3. Development of Numerical Model
3.1 Reinforced Concrete Beam Properties

In this research 3 types of the reinforced concrete beam are made. They are grouped into, 1 RC beam which is not exposed to fire, 1 RC beam after the fire and 1 RC beam after fire strengthened in flexure, which is termed by NB, AFB, and CAFB respectively. The whole models are 250 mm x 150 mm 74 x 1500mm in dimension with 4 flexural reinforcements and stirrups in 450mm along in beam 75 from each support. Models were analyzed with nonlinear finite element method using ATENA 76 v.2.1.10 software. The FE model is calibrated against recent experimental results. Once validated, the model is used to examined stiffness, ductility, crack propagation and type of failure. There are six (6) models of the reinforced concrete beam which compares to the experimental results conducted by Ngudiyono [4]. All of the beams have 150x250mm2 in dimension with 1500mm of length. Beam support is pin and roll subjected by incremental monotonic point loading of 20 kN of weight at two points from 450mm from each support until it reached ultimate strength.

Table 1. Properties of RC Beam Model

| No | Beam Index | Number | Dimension (mm) | Reinforcement | CFS                  |
|----|------------|--------|---------------|---------------|---------------------|
|    |            |        |               | Main | Stirrups | Flexural Strengthening, L=1 m |
| 1  | NB         | 2      | 150x250x1500, s = 25 | D10 | D8-100 | -                        |
| 2  | AFB        | 2      | 150x250x1500, s = 25 | D10 | D8-100 | -                        |
| 3  | CAFB       | 2      | 150x250x1500, s = 25 | D10 | D8-100 | Flexural Strengthening, L=1 m |

Figure 7. Cracked Beam Element (Source: Park & T Paulay, 1990)
3.2 Development of Numerical Model

In order to develop the numerical model, RC beam used the following elements:

Reinforced Concrete
Concrete was modeled as a 3D solid element which is brick element CCIsoBrick $<xxxxxxx_x>$ with 8 nodal. CCIsoTruss$<xx_x>$ elements were used to model the steel reinforcement. At least 2 (two) nodal are needed to build this element which becomes isoperimetric elements integrated by Gauss.

Carbon Fiber Strips (CFS)
Carbon Fiber Strip (CFS) was modeled using a solid 3D element with 8 nodal as CCIsoBrick $<xxxxxxx_x>$ which can be shown in Figure 9. The perfect bond assumption was used in this model. Therefore, the CFS element uses the same nodal as RC Beam.

RC Beam which has been degraded by high temperature named After fire RC Beam was modeled into 3 layers using temperature distribution trajectory up to 8000C developed by Castillo 1990 [11] and concrete compressive strength distribution under temperature load relationship [12].
Table 2. Concrete Material Parameters

|         | NB | AFB and CAFB     |
|---------|----|-----------------|
|         |    | Layer 1 Depth 25mm | Layer 2 Depth 40mm | Layer 3 Depth 60 mm |
| $f'_c$  | 28.29* | -10,60875**   | -14,145**   | -15,65**   |
| $v$     | 0.2  | 0.2             | 0.2         | 0.2         |
| $E_c$   | 31638,3801 | 20514,6645 | 23423,9360 | 24520,8142 |
| $f't$   | 2,4832521 | 1,29144       | 1,564350    | 1,673432   |
| $G_f$   | 6,209E-005 | 3,229E-005   | 3,911E-005  | 4,184E-005 |
| $e_{cp}$| -0.0008942 | 0.0005172   | 0.0006039   | 0.0006382  |
| Fixed crack | 0.7       | 0.7           | 0.7         | 0.7        |
| $f_c0$  | -20 | -7,07333       | -9.43       | -10,43333  |

Compressive Strength tested by Ngudiyono (2001).
** Compressive Strength converted from Gustaferro (1998).

Reinforcement was modeled in discrete using a CCREinforcement2 material with truss element. (see Figure 15), while Carbon Fiber Strips was modeled using material properties as described in Ngudiyono (2001) in Table 4 and shown in Fig 16.
Table 3. Data – data material CFS dan adhesive

| Material | Type       | Elastic Modulus (E), MPa | Tensile Strength (fu), MPa |
|----------|------------|---------------------------|----------------------------|
| CFS      | Sika Carbodur S512 | 155000                   | 2400                       |

4. Results and Discussion

The numerical model showed that after fire reinforced concrete beam can be modeled using S-Beta Material in ATENA software. The numerical research results show that the ultimate flexural strength of NB, AFB, and CAFB are 56 kN, 52 kN, and 60 kN. Following figures 15(a-d) show the load-displacement and crack pattern of every numerical model for before-fire reinforced concrete beam (BN), after-fire reinforced concrete beam (BPB), BPB with CFS flexural strengthening (BFS).

Figure 15. Load vs. Displacement of Numerical Model

Strengthening method utilized Carbon Fiber Strip (CFS) on after fire beam could decrease ductility but increase the stiffness numerically and experimentally. Thus, it could not block some diagonal cracks that happened and caused brittle failure. The deflection value at the ultimate loading at 1/3 for NB, AFB, and CAFB in the experiment was higher than in numeric. The value of stiffness obtained NB, AFB, and CAFB in the experiment was higher than the sample from the numeric result namely 57%, 64%, 45%. While the ductility value obtained NB, AFB, and CAFB from the experiment was also smaller about 59%, 41%, and 17% in comparison to its numerical. The strain values when the ultimate loading at 1/3 span on beam CAFB respectively 0.0066076 and 0.007758 was bigger than AFB namely 0.0007 and 0.000079 both X and Y direction, while ductility value of stress at the ultimate loading at 1/3 span
obtained on CAFB numeric was also bigger than AFB numeric both x and y-direction. S- Beta material in ATENA program was sensitive enough towards elasticity modulus. Even though, the material parameters varied, obtained numeric beam was still stiffer compared to the experimental beam. The significant difference in the stiffness between numerical model and experimental results possibly due to the assumption of smeared reinforced for stirrups and the perfect bond between reinforcement and concrete. For the CAFB model, stiffness also became higher since the bonding between CFS and concrete was assumed as perfect bond with stiffness factor k=1. This condition possibly also caused by the meshing of the CFS element which is not ideal due to ill condition element, since the ratio of CFS element dimension is very high compared to the meshing for concrete.

![The crack pattern of NB](image1)
![The crack pattern of AFB](image2)
![The crack pattern of CAFB](image3)

Figure 16. Crack Patterns of NB-AFB and CAFB Model

Figure 16 shows the difference in the numerical model. The crack of AFB is more significant than NB which can show the effects of concrete strength decreasing after the beam subjected by the high-temperature load. For CAFB, the crack patterns look more distributed. However, the maximum crack width is smaller than NB and AFB, which can show the influence of CFS strengthening (see Figure 19), meanwhile, the crack width of after-fire RC beam AFB is wide than NB.

![ Crack Width vs Load of NB-AFB-CAFB](image4)

Figure 17. Crack Width vs. Load of NB-AFB-CAFB

5. Conclusion and Suggestions

5.1. Conclusion
S-Beta Material utilized in ATENA for nonlinearity material modeling for After Fire Reinforced Concrete Beam show a good agreement with the results from experimental results. The approach of 3-layer modeling of compressive strength concrete degradation distribution trajectory and the relationship of temperature load and percentage of strength degradation gave a good numerical model that can verge
the real condition. Even though the stiffness comparison between the beam models are different, but the displacement-load curve and the crack pattern results on a good agreement also.

5.2. Suggestion
Its needed to input the real bonding behavior between CFS and concrete layer by experimenting with bonding failure. Furthermore, it is essential to improve the discretization of CFS to eliminate the ill element condition of CFS, but this condition will need a more significant number of meshing which significantly demanding better version of software and computer’s capacity should be avoided whenever possible. If required they should be used only for brief notes that do not fit conveniently into the text.

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