Fracture To Failure
A Fracture Mechanics Approach For Bridge Failure Analysis

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ABSTRACT

The development of infrastructure, includes the bridge, takes important role in improving the progress of sustainable development. Hence, all the parts of infrastructure should be placed and constructed safely and sustainable. However, the failure of structures has been coloring the world of infrastructure development for many decades. Some cases told that the failure of structure extremely caused by crack and fracture that bring the structure failure and even collapse. Fulfilling the need of safe and sustainable structure, the fracture mechanics gives solution to answer the demand of safe structure, especially bridge structure, by considering fracture phenomenon at all structural elements. This paper will take a review on fracture problem which causes failure, in context of bridge analysis failure that is approached by fracture mechanics. The two cases which become reviewed in this paper are the picture of structural failure analysis in macro and micro scale. The collapse of Schoharie Creek Bridge describes the failure of structure in macro scale and the pull-out specimen's failure modeling will give enrichment of understanding of failure analysis in micro scale. This paper meets some conclusions: (a) The fracture mechanics gives solution to answer the demand of safe structure by considering fracture phenomenon at all structural elements. The fracture mechanics becomes a significant tool to get a safe and sustainable structure, especially bridge structures; (b) The finite element modeling by Swenson and Ingraffea has successfully simulated the initial of crack emerging, the crack propagation, and also the fracture phenomenon during the collapse of the bridge. Swenson and Ingraffea (1991) recommended the fracture mechanics to analyze the failure of the structure and to design the structure that is safe and effective, and (c) Susilorini has noted that pull-out specimen's failure modeling may describe failure analysis in micro scale clearly. Some theories have established by Susilorini: (a) Fracture criterion of fiber cementitious composites determined by critical J-Integral; (b) Critical J-Integral take a role as significant complementary energy; (c) Finite element model delivers appropriate fracture criterion, that is critical J-Integral; (d) Some new equation improvement retrieved from Marshall and Cox; and (5) Crack arrester will exist in every final of slip stage, hence the critical J-Integral is going to be emerged in strain-hardening stage.

Keywords: *fracture, failure, analysis*

1. INTRODUCTION

The development of infrastructure takes important role in improving the progress of sustainable development. Hence, all the parts of infrastructure should be placed and constructed safely and sustainable. The bridge, absolutely, is a major part of this development. Undoubted, the bridge will make a tight engagement among the nation in Indonesia. A question still left behind, what and how the safe structural design is. Answering this question, a fracture mechanics approach has been explored since fifty years ago by Bresler and Wollack, 1952, Kaplan, 1961, etc (Bazant, 1992). Since its earlier improvement, the fracture mechanics is a solution to prohibit a catastrophic failure of structure. When a structure is constructed, a safe design is the most important requirement to assure the safety criterion.

The concrete structures are the most popular type of structures in the world compared to other type of structures. Along it advantages, concrete is found to be very brittle. Since the fracture has been emerged, crack propagation will follows and bring the failure of whole structure as a final result. Therefore, according to Bazant (1992), the failure of concrete structures should consider the strain-softening related to distributed cracking, localized crack that grows to larger fracture prior to failure, and bridging stresses at the fracture front. Then, the suppression of fracture of concrete must be implemented by improving higher toughness and higher tensile ductility (Li and Wang, 2005). Some innovations have been applied (Fischer and Li, 2004) such as Fiber Reinforced Concrete (FRC), High Performance Fiber Reinforced Cementitious Composites (HPRFCC) which is known as Engineered Cementitious Composites (ECC). While the conventional design of concrete structures practiced by structural engineer in structural design, the fracture mechanics approach then being introduced into the concrete design. The main principle of fracture mechanics is implementing the failure criterion of concrete structure. By using fracture mechanics, the design is believed getting more safety margin for structure and improving economic value as well as structural benefit.

A safe design of structure means a proper-accurate design of structural elements of the structure itself. The conventional design of concrete and reinforced concrete (as well as FRC, HPRFCC, and ECC) is based on the ultimate-limit analysis and service performance analysis that uses strength-based failure criterion for determining the loading capacity of the structures. By fracture mechanics approach, the ultimate-limit analysis calculates loading beha

vior of structure by combining stress equilibrium, strain compatibility, and constitutive laws of materials at failure (Shah,et.al, 1995). Obviously, the fracture mechanics gives solution to answer the demand of safe structure, especially bridge structure, by considering fracture phenomenon at all structural elements.

This paper will take a review on fracture problem which causes failure, in context of bridge analysis failure that is approached by fracture mechanics. The two cases of Schoharie Creek Bridge collapse (Li and Wang, 2005) and the pull-out specimen's failure modeling (Susilorini, 2007b, c) became studied to retrieve the essence of fracture mechanics role in failure analysis.

2. FRACTURE MECHANICS AND FAILURE ANALYSIS BASED ON FRACTURE MECHANICS

The failure of structures has been coloring the world of infrastructure development for many decades. Some cases told that the failure of structure extremely caused by crack and fracture that bring the structure failure and even collapse. The structural failure of infrastructure can be found for examples in cases of failure of rail road on 1860-1870 in UK (Broek, 1982); the collapse of Montrose suspension bridge on 1830 (Broek, 1982); the failure of Kings bridge in Melbourne on 1962 (Rolfe and Balsom, 1977); the collapse of Schoharie Creek Thruway on 1987 (Li and Wang, 2005); infrastructure's collapse by earthquake in Kobe on 1994 (Li and Wang, 2005); the collapse of Mississippi bridge (Figure 1) on August 2007 (Elswort, 2007); the collapse of the bridge in Fenhuang China, the Hunan Province on August 2007 (www.bbc.co.id).

Figure 1. The collapse of Mississipi Bridge on Agustus 2007
(Ellsworth, 2007; the picture is downloaded on 5 Agustus 2007 from www.telegraph.co.uk.)

Those cases of structural failure mentioned above have emphasized that the structural design should cover the possibility of crack and fracture formation that may bring the structure to become collapse. It means, the structure has to resist loads and failure parts as far as it fulfil the damage tolerant. In this part, the fracture mechanics takes a role in suppressing the failure of structure (Li and Wang, 2005). The fracture mechanics may be defined as a study about response and failure of structure caused by crack formation and propagation (Shah, et. al, 1995). According to Bazant (1992), the fracture mechanics is a failure theory that implements the energy criterion and crack propagation. It should be noted that the term of 'fracture' is not similar to 'crack'. When a crack emerged in a body, the crack will be improved to become fracture (Broek, 1982). Hence, a fracture can be considered more as a phenomenon. McAdam (in Nadai, 1950) noted that material will get failure when one of its principal stresses reaches maximum value. The statement mentioned by McAdam based on "Maximum Stress Theory" (Nadai, 1950; Timoshenko, 1976) that a maximum principal stress will determine the failure of the structure. The two cases which become reviewed in this paper are the picture of structural failure analysis in macro and micro scale. The collapse of Schoharie Creek Bridge describes the failure of structure in macro scale and the pull-out specimen's failure modeling will give enrichment of understanding of failure analysis in micro scale.

3. THE CASE OF SCHOHARIE CREEK BRIDGE COLLAPSE, NEW YORK, 1987 (SWENSON DAN INGRAFFEA, 1991)

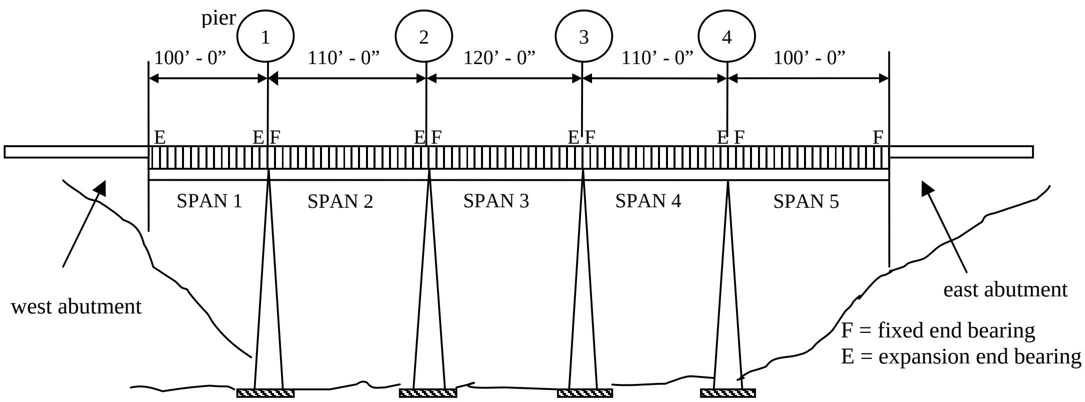

Figure 2. Elevation of Schoharie Creek Bridge
(Redraw from: Swenson dan Ingraffea, 1991)

The collapse of Schoharie Creek Bridge (Figure 2) in New York, 5 April 1987 has pointed an important concern about failure analysis based on fracture mechanics. Swenson and Ingraffea (1991) have learnt with official deep study from the authority (Wiss and Rutledge, 1987). The analysis of Schoharie Creek Bridge's failure is implemented by fracture mechanics by Swenson and Ingraffea (1991) with finite element modeling. The modeling is built on the base of size-effect concept in linear Elastic Fracture Mechanics (LEFM) and Non Linear Fracture Mechanics (NLFM).

It is necessary need to know what the cause root of the Schoharie Creek Bridge's failure. The cause root of this case is the existence of scouring under the pier. The loss of the soil under the pier cause stress redistribution and emerge tension stress in plinth. The existence of tension stress cause crack. The crack propagates and causes fracture. Unstable formation of fracture happened. This unstable fracture will generate unstable crack propagation and finally, get the whole structure of bridge collapse. Some important factors have become notes in this case review: (a) The reinforcement in the body of bridge's pier isn't designed appropriately, and (b) On 1955, one year after the bridge was operated, an observation found the formation of vertical crack in all plinth but it was neglected.

The finite element modeling by Swenson and Ingraffea (1991) is built both by 2D and 3D analysis. The model has successfully simulated the initial of crack emerging, the crack propagation, and also the fracture phenomenon during the collapse of the bridge. Swenson and Ingraffea (1991) recommended the fracture mechanics to analyze the failure of the structure and to design the structure that is safe and effective. It is proved that the fracture mechanics becomes a significant tool to get a safe and sustainable structure, especially bridge structures

4. PULL-OUT SPECIMEN'S FAILURE MODELLING (SUSILORINI, 2007B, C)

The fracture mechanics takes important role in fiber cementitious composites (FRC). The improvement of fiber cementitious composites such as FRC, HPRFCC, and ECC is engaged to the fiber application such as nylon, which is categorized as synthetic fiber. The fiber existence will determine whole fiber-reinforced cementitious composite performance. For certain reasons, nylon fibers in cementitious composites will improve strain-hardening property (Susilorini, 2007a), tension strength, and elastic modulus. Some researches noted better performance of ECC with various synthetic fiber surfaces (Li, Chan, and Wu, 1994), high performance as alike steel performance (Clements, 2002), and higher compressive stress for irradiated nylon fiber by gamma (Martinez-Barera, 2006). The nylon fiber has a special characteristic of multiple constrictions at stretching condition (Nadai, 1950) called 'yield point elongation' that has magnitude of 200%-300% of initial fiber length. The multiple constrictions caused by nylon viscosity appeared by 'jagged' phenomenon of stress-strain or load-displacement curves (Avarett, 2004; Susilorini, 2007).

Bazant (1992) has stated fracture mechanics main concept of this micro scale case study of failure analysis. According to Bazant, the failure of structure is engaged to strain-softening and strain-hardening condition due to crack distribution. The crack, in which localized, may propagate and develop to fracture and then get failure. Some efforts should be done to reduce the possibility of fracture existence such as increasing toughness and tension ductility of structure by applying the fiber in cementitious composites (Li and Wang, 2005).

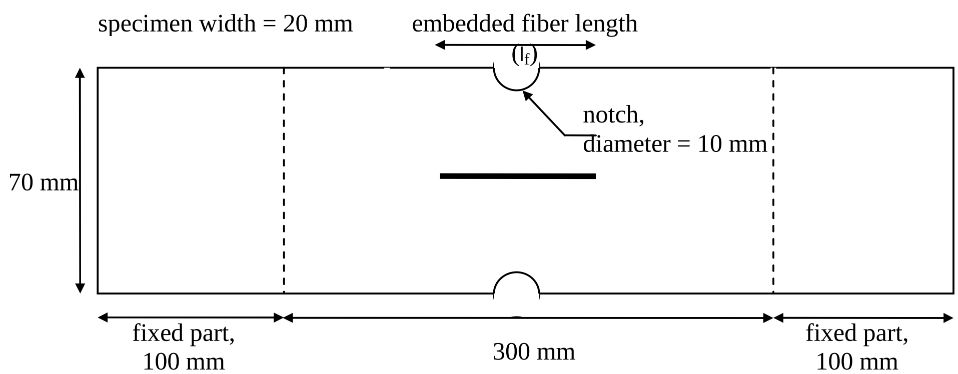

Figure 3. The fractured pull-out specimen's design

Susilorini (2007b, c) has noted that pull-out specimen's failure modeling may describe failure analysis in micro scale clearly. The research of Susilorini (2007b, c) conducted by experiment and analytical methods. The experiment method applied fractured specimen with embedded nylon fiber described by Figure 3. The pull-out test conducted by computerized Universal Testing Machine "Hung Ta". The nylon 600 fiber is local made with 1.1. mm in diameter and embedded length 100 mm. Mix design for cementitious matrix is cement : sand : water ratio of 1:1:0.6. Analytical method applied by modeling and formulation of theoretical model (Susilorini, 2007) and followed by finite element modeling to find critical J-Integral as a fracture criterion. The calculation of critical J-Integral of model will be compared to the experimental results. The experiment results has shown several stages during fracture pull-out process: (a) Stage of pre-slip, (b) Stage of slip, (c) Stage of transition, and (d) Stage of strain-hardening with 'jagged' phenomenon. The review found that fracture phenomenon happened during the pull-out process. The stress-strain ($\sigma-\varepsilon$) curves of pull-out experiment results are used to analytical calculation of critical J-Integral by improving the Marshall and Cox equation. The finite element modeling of fractured pull-out specimen is built by ADINA v. 8.3. The model implements fracture feature to calculate critical J-Integral and rubberlike material – Ogden to raise Poisson's effect (Figure 4). The critical J-Integral value from finite element model then being verified by the experiment value. The results of experiment are similar to analytical with critical J-Integral value ranged 18,000-27,000 N/mm. It is fit also to critical J-Integral value from finite element model, 18,648.60 N/mm.

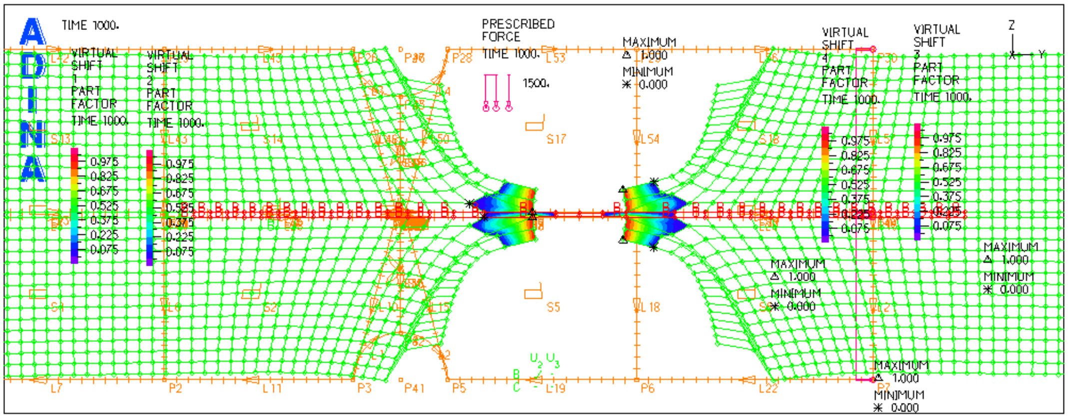

Figure 4. The finite element model of fractured pull-out specimen's at the time of specimen's failure

Some theories have established by Susilorini (2007b, c): (a) Fracture criterion of fiber cementitious composites determined by critical J-Integral; (b) Critical J-Integral take a role as significant complementary energy; (c) Finite element model delivers appropriate fracture criterion, that is critical J-Integral; (d) Some new equation improvement retrieved from Marshall and Cox; and (5) Crack arrester will exist in every final of slip stage, hence the critical J-Integral emerged in strain-hardening stage. It is shown that the pull-out specimen's failure modeling by Susilorini (2007b, c) already give clear understanding of failure analysis in micro scale.

5. CONCLUSIONS

This paper meets some conclusions:

1. The fracture mechanics gives solution to answer the demand of safe structure by considering fracture phenomenon at all structural elements. The fracture mechanics becomes a significant tool to get a safe and sustainable structure, especially bridge structures

2. The finite element modeling by Swenson and Ingraffea (1991) has successfully simulated the initial of crack emerging, the crack propagation, and also the fracture phenomenon during the collapse of the bridge. Swenson and Ingraffea (1991) recommended the fracture mechanics to analyze the failure of the structure and to design the structure that is safe and effective.

3. Susilorini (2007b, c) has noted that pull-out specimen's failure modeling may describe failure analysis in micro scale clearly. Some theories have established by Susilorini (2007b, c): (a) Fracture criterion of fiber cementitious composites determined by critical J-Integral; (b) Critical J-Integral take a role as significant complementary energy; (c) Finite element model delivers appropriate fracture criterion, that is critical J-Integral; (d) Some new equation improvement retrieved from Marshall and Cox; and (5) Crack arrester will exist in every final of slip stage, hence the critical J-Integral is going to be emerged in strain-hardening stage.

REFERENCES

Avarett, RD (2004). "**Fracture Mechanics of High Performance Nylon Fibers**", Thesis, Georgia Institute of Technology, USA.

Bazant, ZP. (1992). "**Fracture Mechanics of Concrete: Concepts, Models, and Determination of Material Properties – State of the Art Report**", Proceedings, First International Conference on Facture Mechanics Concrete Structure (Framcos 1), (Ed. Bazant, ZP), Colorado, USA, pp.6-140.

Broek, D. (1982). "**Elementary Engineering Fracture Mechanics**", Martinus Nijhoff Publishers, The Hague, Boston, London.

Clements, M. (2002). "**Synthetic as Concrete Reinforcement**", *Concrete Magazine*, United Kingdom, September, 37-38.

Elsworth, C. (2007). "**Mississippi Bridge Collapse Survivors Speak**", Telegraph co.uk, taken August 5 from www.telegraph.co.uk.

Fischer, G., Li, V.C. (2004). "**Effect of Fiber Reinforcement on the Response of Structural Members**", *Proceedings Framcos-5*, (eds. Li, et. al). Ia-Framcos, 831-838.

Li, V.C., and Wang, S. (2005). "**Suppression of Fracture Failure of Structures by Composite Design based on Fracture Mechanics**", corresponding paper in Compendium of Papers CD ROM, Paper 5543.

Li, V.C., Chan, Y.W., Wu, H.C. (1994). "**Interface Strengthening Mechanism in Polymeric Fiber Reinforced Cementitious Composites**", *Proceedings of International Symposium on Brittle Matrix Composites*, (eds. Brandt, A.M, Li, V.C., Marshall, L.H), IKE and Woodhead Publ, Warsaw, 7-16.

Martinez-Barrera, G. (2006). "**Concrete Reinforce with Irradiated Nylon Fibers**", Journal of Material Research, Vol.21, No. 2, February, pp. 484-491.

Nadai, A. (1950). "**Theory of Flow and Fracture of Solids**", Volume I, McGraw-Hill Company. Inc, New York, USA.

Shah, S.P., Swartz, S.E., Ouyang, C. (1995). "**Fracture Mechanics of Concrete: Applications of Fracture Mechanics to Concrete, Rock, and Other Quasi-Brittle Materials**", John Wiley & Sons, Inc., New York.

Susilorini, Retno, M.I. (2007a). "**Model Masalah Cabut-Serat Nylon 600 Tertanam dalam Matriks Sementitis yang Mengalami Fraktur**", Disertasi, Parahyangan Catholic University, Bandung.

Susilorini, Retno, Rr. M.I. (2007b). "**Analisa Kegagalan Struktur Berbasis Fraktur Untuk Penyelamatan Bumi dan Pembangunan Berkelanjutan**", Seminar Sehari Kehutanan "Save the Forest Save the Earth", Fakultas Teknik Unika Soegijapranata, 2008.

Susilorini, Retno, Rr. M.I. (2007c). "**Integral-J Kritis untuk Model Elemen Hingga pada Cabut Serat Fraktur Nylon 600**", Prosiding Seminar Nasional Tiga Roda Forum "Perkembangan Terkini Teknologi dan Rekayasa Konstruksi Beton di Indonesia", Hotel Bumi Karsa - Bidakara, Jakarta, pp.1-14.

Swenson, DV., dan Ingraffea, AR. (1991). "**The Collapse of the Shoharie Creek Bridge: a Case Study in Concrete Fracture Mechanics**", International Journal of Fracture, "Current trends in Concrete Fracture Research" (ZP Bazant, ed), Vol .51, pp. 73-92.

Timoshenko, S. (1976). "**Strength of Material – Part II: Advanced Theory and Problems**", Robert E Krieger Publishing Company, Huntington, New York.