MODELLING OF THE BEHAVIOUR OF STEEL FIBRE REINFORCED CONCRETE (SFRC) BEAMS

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ABSTRACT

Concrete has the lowest ratio between cost and strength as compared to others available materials and hence it is still the most widely used materials in construction. However, the brittle behaviours of concrete has affected the reliability and durability of structures. So, steel fibres are suggested adding into conventional concrete to improve the structural behaviours. The structural behaviours of two-span continuous steel fibre reinforced concrete (SFRC) beam were studied in present investigation using non-linear finite-element analysis. Finite element program, Abaqus was adopted to perform the finite element analysis of present investigation. The effects of steel fibres in concrete were modelled by SFRC constitutive model proposed by Lok and Xiao (1999). Initially, the validation and calibration works FE predictions were performed by using experimental results. After the good correlation among FE predictions and experimental results were achieved, parametric modelling was carried out using by two key parameter; stirrups spacing (i.e. stirrups spacing increment, SI) and fibre contents (i.e. volume fraction, V_f). The settings were designed to examine the potential of steel fibres to serve as a part of stirrups. Beside these, other key structural parameter included strength, ductility, cracking propagation and modes of failure were determined through the investigation. The findings showed that the mentioned structural behaviours of beam were improved by inclusion of steel fibres significantly at an optimum amount of fibres dosage.

ABSTRAK

Konkrit mempunyai nisbah yang paling rendah di antara kos dan kekuatan berbanding dengan bahan-bahan binaan lain. Oleh itu, ia masih merupakan bahan binaan yang paling banyak digunakan dalam pembinaan. Walaubagaimanapun, tingkah laku konkrit yang secara rapuh mengesankan kebolehpercayaan dan ketahanan struktur. Jadi, penambahan gentian keluli ke dalam konkrit telah dicadang untuk meningkatkan tingkah laku struktur. Tingkah laku struktur rasuk berentang dua yang diperkukuhkan oleh gentian keluli atau dikenali sebagai "steel fibre reinforced concrete (SFRC)" telah dikaji dalam penyiasatan ini menggunakan analisis unsur terhingga yang tidak linear. Program unsur terhingga, Abaqus telah diguna untuk melaksanakan analisis unsur terhingga dalam penyiasatan ini. Kesan gentian keluli dalam konkrit telah dimodelkan oleh SFRC juzuk model yang dicadangkan oleh Lok dan Xiao (1999). Pada mulanya, pengesahan dan penentukuran kerja-kerja ramalan unsur terhingga telah dijalankan dengan menggunakan keputusan eksperimen. Selepas korelasi yang baik antara ramalan FE dan keputusan eksperimen telah dicapaikan, model parametrik dijalankan menggunakan oleh dua parameter utama; susunan stirrups (penambahan jarak stirrups, SI) dan kandungan gentian keluli (pecahan isipadu, Vf). Tetapan direka untuk memeriksa potensi gentian keluli untuk berkhidmat sebagai sebahagian daripada stirrups. Selain itu, parameter struktur utama yang lain termasuk kekuatan, kemuluran, keretakan pembiakan dan mod kegagalan telah ditentukan melalui kajian. Hasil kajian menunjuk bahawa tingkah laku struktur rasuk telah ditingkatkan secara ketara melalui penambahan gentian keluli dengan amaun gentian keluli yang optimum.

TABLE OF CONTENTS

		Page
SUPERVISOR'S DECLARATION		ii
STUDENT'S DECLARATION		iii
ACKNOWLEDGEMENTS		v
ABSTRACT		vi
ABSTRAK		vii
TABLE OF CONTENTS		viii
LIST OF TABLES		xi
LIST OF FIGURES		xii
LIST OF SYMBOLS		xv
LIST OF ABBREVIATIONS		xvi
CHAPTER 1	**INTRODUCTION**	
1.1	Background of Study	1
1.2	Problem Statement	2
1.3	Study Objective	3
1.4	Scope of Study	3
1.5	Significant of Study	5
CHAPTER 2	**LITERATURE REVIEW**	
2.1	Introduction	6
2.2	Overview of Fibres	7
2.3	Structural Behaviours	8
	2.3.1 Flexural Strength	8
	2.3.2 Ductility	9
	2.3.3 Cracking Propagation	11
	2.3.4 Mode of Failure	11
	2.3.5 Plastic Hinge Formation	14

	2.3.6 Strain Hardening and Strain softening	15
2.4	Finite Element Analysis (FEA)	16
2.5	Review of Previous Modelling Work on SFRC	17
	2.5.1 Review Paper 1	17
	2.5.2 Review Paper 2	18
	2.5.3 Review Paper 3	20
	2.5.4 Review Paper 4	20
	2.5.5 Review Paper 5	21
2.6	Summary	21
CHAPTER 3	**METHODOLOGY**	
3.1	Introduction	23
3.2	Abaqus/CAE	23
	3.2.1 Preface	23
	3.2.2 Concrete Model Available in Abaqus	24
	3.2.2.1 Smeared Cracking Concrete Model	24
	3.2.2.2 Brittle Cracking Concrete Model	27
	3.2.2.3 Concrete Model Selection	29
	3.2.2.4 Steel Model	30
3.3	Constitutive Model for SFRC	32
	3.3.1 Lok and Xiao (1999) SFRC Model	32
	3.3.2 Compression Model	32
	3.3.3 Tension Model	33
3.4	Analysis Procedure	34
	3.4.1 Static Analysis	34
	3.4.2 Dynamic Analysis	35
	3.4.3 Selection of Analysis Procedure	35
3.5	Failure Criterion	36
3.6	Scope of Investigation	36
3.7	Numerical Modelling in Abaqus	39
3.8	Summary	42

CHAPTER 4 RESULTS AND ANALYSIS

4.1 Introduction 44

4.2 Calibration with Experimental Results 44

4.2.1 Result of Calibration 46

4.3 Parametric Studies 48

4.3.1 Load-deflection Curves 50
4.3.2 Strength 53
4.3.3 Ductility 53
4.3.4 Cracking Patterns 54
4.3.4.1 Principal Stain Contours 54
4.3.4.2 Principal Strain Vectors 57
4.3.4.3 Deflected Shapes 60
4.3.5 Comparative Study with Control Specimen Using Non-Dimensional Ratios 63
4.3.5.1 Strength Ratio 64
4.3.5.2 Ductility ratio 65
4.3.5.3 Energy Absorption Ratio 66

4.4 Summary 67

CHAPTER 5 CONCLUSION AND RECOMMENDATION

5.1 Conclusion 69

5.2 Recommendation and Limitations 71

REFERENCES 72

APPENDICES

A Parameter adopted for Tensile Stress Strain Relation of SFRC (Lok and Xiao, 1999 SFRC Constitutive Model) 78

B Calibration Works 81

LIST OF TABLES

Table No.	Title	Page
1.1	The steel fibre contents and stirrup spacing increment that conducted in parametric study	4
3.1	Parametric study of SFRC beam	37
4.1	Tensile stress-strain relationship for RC beams with no fibres and SFRC beams with V_f= 1%	45
4.2	Results summary of load-deflection curves for calibration work	47
4.3	Tensile stress-strain properties for plain concrete and SFRC	49
4.4	Result summary for beams with SI = 0%, 50% and 100%	52

LIST OF FIGURES

Figure No.	Title	Page
2.1	Shapes of steel fibres	7
2.2	Load-deflection curve of plain concrete and SFRC with 1% addition of fibres from a monotonic loading test	10
2.3	Shear Failure of Beam	12
2.4	Flexural failure of beam	12
2.5	Mode of failure of sample beams with different content of fibres	13
2.6	Normal stress distribution in a rectangular beam when section c-c has become fully plastic	14
2.7	Types of stress-strain response	15
2.8	Types of stress-strain response of SFRC	16
2.9	Post cracking tension constitutive law of SFRC adopted in simulation	18
2.10	Tension stress-strain model for SFRC adopted in parametric modelling	19
3.1	Uniaxial behaviour of plain concrete	25
3.2	Tension stiffening model	25
3. 3	Yield and failure surface in plane stress	26
3.4	Shear retention model	27
3.5	Rankine criterion in plane stress	28
3.6	Post-failure stress-strain curve	29
3.7	Piece-wise linear form of the shear retention model	29
3.8	Stress-strain relations for steel material	31

3.9	RC beam modelled using stringer reinforcement	31
3.10	Tensile Stress-Strain Behaviour	34
3.11	Arrangement and dimension of SFRC specimen beam	37
3.12	Flowchart of the present investigation	38
3.13	Numerical modelling process of the present investigation	39
3.14	Half of the specimen modelled in Abaqus with defined boundary condition along symmetrical	40
4.1	Tensile stress-strain diagram adopted for calibration work	45
4.2	Loading histories input for monotonic loading	46
4.3	Load-deflection curves for calibration work	47
4.4	Kinetic energy plots to determine failure for beams	48
4.5	Stress–strain relations in tension adopted for numerical modelling of SFRC	49
4.6	Load-deflection curves for beams with SI = 0%, 50% and 100%	50
4.7	Principal strain contours of beams with SI = 0%	55
4.8	Principal strain contours of beams with SI = 50%	56
4.9	Principal strain contours of beams with SI = 100%	57
4.10	Principal strain vectors of beams with SI = 0%	58
4.11	Principal strain vectors of beams with SI = 50%	59
4.12	Principal strain vectors of beams with SI = 100%	60
4.13	Deflected shapes of beams with SI = 0%	61
4.14	Deflected shapes of beams with SI = 50%	62
4.15	Deflected shapes of beams with SI = 100%	63

4.16	Ratio of maximum load to that of the control specimen (SI = 0%, V_f = 0%) versus steel fibre volume fraction graph	64
4.17	Ratio of yield load to that of the control specimen (SI = 0%, V_f = 0%) versus steel fibre volume fraction graph	65
4.18	Ratio of ductility ratio to that of the control specimen (SI = 0%, V_f = 0%) versus steel fibre volume fraction graph	66
4.19	Ratio of energy absorption to that of the control specimen (SI = 0%, V_f = 0%) versus steel fibre volume fraction graph	67

LIST OF SYMBOLS

V_f	Volume fraction of steel fibres
σ	Stress
f_t	The concrete tensile strength
f_{tu}	The post-cracking residual tensile stress
ε	Strain
ε_{t0}	Corresponding ultimate strain
ε_{t1}	The cracking strain
η	Fibre orientation factor
L/d	Aspect ratio of the steel fibre
Es	Elastic modulus of steel fibre
τ_d	Bond stress of steel fibre
P_y	Yielding load
P_{max}	Maximum load carrying capacity
P_u	Ultimate load
δ_y	Deflection at yield
δ_{Pmax}	Deflection at maximum load
δ_u	Ultimate deflection
μ	Ductility ratio
$\mu_{,0}$	Ductility ratio of control beam
E_a	Energy absorption
$E_{a,0}$	Energy absorption of control beam

LIST OF ABBREVIATIONS

3D	Three Dimensional
EC 2	Eurocode 2
FE	Finite Element
FEA	Finite Element Analysis
FES	Finite Element Software
NLFEA	Non-linear Finite Element Analysis
SFRC	Steel Fibre Reinforced Concrete
SI	Increased in the Stirrups Spacing

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND OF STUDY

The using of horsehair in mortar and straw in mud bricks shows that the history of fibre-reinforced materials are since ancient times (Jain and Kothari, 2012). In the early 1900s, asbestos fibres were used in concrete to improve the performance of convention concrete. However, asbestos were believed that will bring health risks to human and several alternative fibres such as steel, glass and synthetic fibres were introduced to replace the asbestos fibres in 1960s.

Fibre reinforced concrete is a composite material that made primarily of hydraulic cements, aggregates and discontinuous, discrete, uniformly dispersed suitable fibres. (ACI Committee 544, 2002). Steel, glass, plastic (i.e polypropylene, graphite etc), carbon and natural (i.e hemp, kenaf etc) fibres are common in the applications recently. Steel fibres are widely in used amongst of these different types of fibres because of the significant effects on structural behaviour of normal concrete. Lok and Xiao (1999) mentioned that the benefits of steel fibres in structural performances include increasing of tensile strength, improvement of cracking resistance and toughness resistance, enhancing of ductility, and inhibiting the crack growth. By these outstanding properties, steel fibres reinforced concrete (SFRC) are widely used in the applications of pavements, marine, mining and tunnelling (Swamy and Lankard, 1974).

The properties of steel fibres are influenced by volume percentage, strength, elastic modulus, and a fibre bonding parameter (i.e. aspect ratio) of the fibres. (ACI Committee 544, 2002). The amount of fibres provided (i.e. volume percentage) perhaps is the most important factor of SFRC. Most of the previous experimental investigations were based on different amount of steel fibres (Oh et al., 1998; Kotsovos et al., 2007; Campione and Mangiavillano, 2008; Zijl and Mbewe, 2013).

The effectiveness of steel fibres as shear reinforcement has been demonstrated in previous experimental research work (Swamy and Bahia, 1985; Oh et al., 1998). The effectiveness of steel fibres as shear reinforcement can reduce the steel congestion and self-weight of strutures.

1.2 PROBLEM STATEMENT

Plain concrete possess the nature of weak in tension and lacks necessary toughness and ductility. However, the issues of ductility is important in the considerations of the detailing of all concrete members during reinforced concrete design (Foster, 2001). The addition of steel fibres in concrete is able to improve the bearing capacity and ductility of the structures.

Experimental works are the best ways to determine the effectiveness of steel fibre. However, based on the case studying on Campione and Mangiavillano (2008), it is found that experimental investigation is time consuming and costly for a number of different parameters to be studied. Thus, numerical modelling is carried out to predict the structures behaviours by computer finite element software. Syed Mohsin (2012) conducted the numerical modelling on the mentioned experiments investigation by increasing the parameters of fibres content. Reliable results were produced by the research in a more visually presentations. Beside this, the stress-strain softening of SFRC is also can be easily analysed in modelling compare to experiment.

Previous investigations of SFRC beams are limited to the structural configuration as simply supported beam (Furlan and Hanai, 1997; Oh et al., 1998; Campione and Mangiavillano, 2008; Meda et al., 2012; Michels et al., 2013 and Hand Zijl and Mbewe, 2013). There is only one investigation on two-span continuous span, i.e. Kotsovos et al. (2007). Due to this prospective, to evaluate the potential of steel fibre in two-span continuous beam; there is a need of expand of this previous works to configuration of continuous beam. The present work will conduct in the configuration of two spans continuous beams under monotonic loading. The outcomes of this research are expected to provide more information in numerical modelling of two spans SFRC beams.

1.3 STUDY OBJECTIVE

There are three objectives to be achieved in this study. Among of them are;

1. Investigate the behaviour of reinforced concrete beams when steel fibre are added into the mix by literature review.
2. Conduct modelling of the beam using finite element software (Abaqus/CAE) and validate it using existing experimental data.
3. Carry out parametric studies for SFRC beams using different volume of fibre percentage and different arrangement of shear reinforcements.

1.4 SCOPE OF STUDY

1. To meet the objectives of the current work, the following scopes of research have been identified:
2. To simulate SFRC two-spans beams with following volume of fibre percentage under monotonic loading by finite element simulation (Abaqus):

3. To obtain the structural behaviours of SFRC two-spans beam as following:
   i) Flexural strength
   ii) Ductility
   iii) Cracking propagation
   iv) Mode of failure
   v) Plastic hinge formation

To conduct calibration and validation of finite element software by existing experiment data.

Table 1.1: The steel fibre contents and stirrup spacing increment that conducted in parametric study.

Stirrup spacing increasing	Volume fraction of steel fibres (v_f)
0%	0%* 1.0%* 1.5% 2.0% 2.5%
50%	0%* 1.0%* 1.5% 2.0% 2.5%
100%	0% 1.0% 1.5% 2.0% 2.5%

Notes:

* = Parameter that consist experimental results.

4. The case study is covered the two-span continuous beam only. The structural design of the sample beams is according to the Eurocode 2. The concrete strength of the sample beams is $30N/mm^2$ (cube strength) and the reinforcing steel bar is $500N/mm^2$.
5. The test configuration is conducted as monotonic loading test.
6. Only hooked-end steel fibres are considered.
7. Numerical modelling is conducted by non-linear analysis.

1.5 SIGNIFICANT OF STUDY

The findings of present investigations have provided more information regarding the structural behaviours of two-span continuous SFRC beams under monotonic loading. Beside this, the outcomes of study also highlight the potential of steel fibres to serve as a part of shear reinforcements. Apart from that, the cracking patterns during failure of SFRC beams are also be provided to the structural designers as a reference that aid to produce a more reliable design.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Concrete has the lowest ratio between cost and strength as compared to others available materials and hence it is still the most widely used materials in construction (Tejchman and Bobiński, 2013). Concrete also possesses many outstanding characteristics such as durable, high efficiency, versatile and fire resistant. However, the brittle behaviours of concrete has affected the reliability and durability of structures greatly. Thus, some improvement methods towards brittleness have been proposed by many scholars. Among of them, it is found that adding fibre into the concrete can significantly enhance the ductility of concrete.

The presence of fibres influences fracture energy requirements during crack propagation. During the pull-out process (i.e. bond failure), fibres in the path of a propagating crack bridges the crack opening and resists further crack growth by dissipating energy (Pompo et al., 1995). The capability of fibres of bridging cracks has increased the ductility of structural members. There are several factors such as fibre quantity, aspect ratio and bond stress are strongly influencing this capability. In order to examine the effectiveness of steel fibre in influencing this capability, experimental investigations and numerical modelling have been carried out. The study were focused structural behaviours of SFRC in the varieties of fibre quantity, aspect ratio and bond stress. The discussion of the structural behaviours are made in this chapter based on the improvement of several structural behaviours such as flexural strength, ductility, post cracking behaviour and etc. The discussion are made based on the basis of findings of experimental and numerical investigations done by scholars. On the other hand, reviews on few numerical investigations by using different finite element program and constitutive model are presented in this chapter.

2.2 OVERVIEW OF FIBRES

ACI Committee 544 (2002) adopted the terminology of FRC by dividing them into four categories based on materials type and they are SFRC, for steel fibre FRC; GFRC, for glass fibre FRC; SNFRC, for synthetic fibre FRC including carbon fibres; and NFRC, for natural fibre FRC. Present investigations are focused on the SFRC where steel fibres also are the most effective for concrete reinforcement and have higher durability compared to other fibres. Classification of steel fibres includes shape, production process and material. Basic material used for the production of the fibres are cold-drawn wire, cut sheet, melt extracted , shaved cold drawn wire and milled from blocks. Most commercially available steel fibres are manufactured from cold drawn steel wire. The shapes available for steel fibres are as shown in Figure 2.1. Among of them, the steel fibres with straight and hooked-end shape are commonly adopted in the investigations of SFRC (Oh et al, 1998; Robin et al, 2002; Olivito and Zuccarello, 2010; Bencardino et al, 2008).

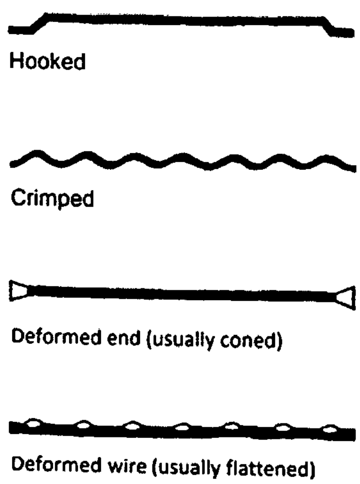

Figure 2.1: Shapes of steel fibres (adapted from Katzer and Domski, 2012)

The shapes of steel fibres will affect the anchorage (i.e. bonding stress) with surround matrix. Trottier and Banthia (1994) discussed that the fibres with deformations only at the ends have the greater energy-absorption capabilities of concrete than those with deformations over the entire length. Aspect ratio (l/d) and volume fraction (Vf) are the most important factors that affect the SFRC properties. Aspect ratio is the ratio of the length to the diameter of fibres. According to Katzer (2006), aspect ratio of fibres that ranges from 20.4 to 152 are available on the world market commonly and aspect ratio varied from 50 to 100 are used in concrete mix generally. Yazıcı et al. (2006) observed that fibres with higher aspect ratio provided higher flexural strength than fibres with lower aspect ratio. On the other hand, increasing aspect ratios may also increase the probability of heterogeneous distribution and flocculation of fibres in concrete mix.

Volume fraction is known as the amount of the fibres in the concrete mix. Volume fraction is the main factor which affect most of the structural behaviour of the SFRC sensitively. Usually, the higher of volume fraction will produce a higher improvement of the structural behaviour. However, the volume fraction is generally limited to 2% due to the workability and fibre spalling problem with high amount of fibre content. (Tang, 2008).

2.3 STRUCTURAL BEHAVIOURS

2.3.1 Flexural Strength

Flexural strength is the parameter to describe the ability of SFRC to resist bending under load without failure. In homogenous materials, flexural strength represents the tensile strength and which is the highest stress experienced within the members at the moment of failure. Most of the materials which include concrete fail under tensile stress before they fail under compressive stress. Concrete has high compressive strength but relatively low tensile strength (around 10 to 20% of compressive strength only) (NRMCA, 2000). So, concrete is usually reinforced with steel reinforcement and the concrete is not designed to resist tension. However, the tensile stress is important in design to estimate the load which cracking will develop.

Generally, study of SFRC is focused in improvement of flexure behaviour since the beneficial effect of fibres is much more significant in tension than that in compression. The fibres in the flexural members will form a tensile skin in the tension zone or near the tension surface and develop plastic behaviour of the tension zone. (Ravindrarajah and Tam, 1984). Swamy and AI-Noori (1975) observed that the beams reinforced with steel fibres had developed the plastic deformations failure.

The flexural strength of SFRC can be obtained through experimental testing (i.e. three-point bending test or four-point bending test). Stress-deflection relationship is obtained through the tests and the flexural strength is determined from the failure load (i.e. peak value) in the stress-deflection curve. Previous investigations show that the adding of steel fibres can improve the flexural strength of the members. (Ravindrarajah and Tam, 1984 Oh et al., 1998; Khaloo et al., 2005; Yazıcı et al., 2007; Campione and Mangiavillano, 2008 and Soutsos et al., 2012). However, few investigations declared that the improvement of the ultimate flexural strength by adding fibres is not so significant (i.e. around 10% only) and especially with lower fibre contents (i.e. Vf $\leqslant$ 1%) (Khaloo et al., 2005 and Soutsos et al., 2012). Khaloo et al. (2005) observed that the fibres does not increase the flexural strength of member significantly but the great improvement in energy absorption capacity. The increasing of energy absorption capacity has improved the ductility and cracks formation of members under loading and this will be discussed in the further section.

2.3.2 Ductility

The behaviour of materials is broadly classified into two categories, brittle and ductile. Ductile materials undergo large strain before fracture while brittle materials will fail at small values of strain. Plain concrete is a brittle material which does not undergo significant deformation before fracture and this is unfavourable for structure uses. So, adding of steel fibres into the concrete mix is proposed to alter the brittle behaviour of plain concrete. The inclusion of steel fibres allows the absorption of certain amount of energy after the maximum load carrying capacity and prevents the brittle failure (Tang, 2008). This energy absorption is associated with the successive pull-out of the fibres which uses large amount of energy (Furlan and Hanai, 1997).

The examination of ductility of SFRC can be through the flexural test as mentioned earlier. Ductility ratio (i.e. ratio of ultimate deflection to deflection at yield) is represented the ductility of the SFRC. Figure 2.2 shows the comparison of load-deflection curve of plain concrete and SFRC with 1% addition of fibres from a monotonic loading test (Campione and Mangiavillano, 2008). From the diagram, it is observed that the brittle behaviour of plain concrete has altered to ductile behaviour which can be explained by the plastic deformation of the SFRC with 1% addition of fibres after yield stage. The plain concrete is failure directly after the yield stage while SFRC with 1% addition of fibres encountered the strain softening after the yield stage before failure. It is also shown both members has close value of deflection at yield stage but SFRC with 1% addition of fibres has four times greater of ultimate deflection to plain concrete which also denotes the four times greater of ductility ability of it. Other investigations includes third-point and four-point bending test also shows that the ductility is significantly enhances by adding steel fibres and the ductile behaviour of SFRC (Furlan and Hanai, 1997; Altun et al., 2007; Soutsos et al., 2012 and Michels et al., 2013).

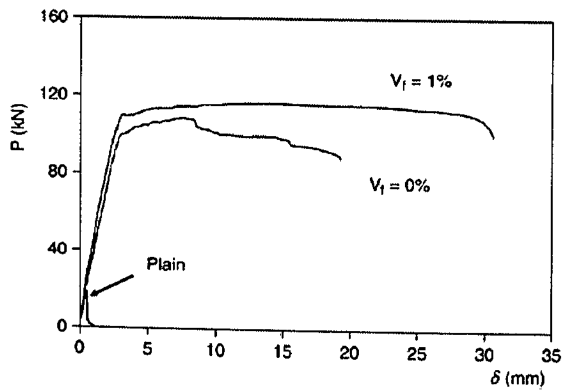

Figure 2.2: Load-deflection curve of plain concrete and SFRC with 1% addition of fibres from a monotonic loading test (adapted from Campione and Mangiavillano, 2008)

2.3.3 Cracking Propagation

Cracking propagation describes the post cracking behaviour of a member. Concrete starts to exhibit nonlinear response after the first crack is formed (Tasdemir et al., 1990). Cracking propagation is the growing of cracks within the member after the initiation of first crack. After the crack initiation stage, existed cracks will extend when applied loads resulting a crack extension force that beyond its crack resistant. Cracking propagation will be continuing through the applied of loading until the ultimate strength is reached at failure stage (Sanford, 2003).

The behaviour of cracking propagation of brittle materials and ductile materials are different. For the brittle materials, the cracking are growing rapidly and fracture immediately. While the crack extension of ductile materials is tardy at initial and also do not lead to the failure immediately. The cracking are growing along with the increasing of applied loadings until the member failures at the ultimate strength. The reduction of cracking propagation of SFRC is governed by the energy absorption capability of fibres. Cracking propagation occurs when the strain energy released provides enough energy required for the crack to grow. Thus, the energy absorption capability of fibres by the pull-out resistance of fibres has reduced the cracking propagation. Investigations shows that the effectiveness of steel fibres in increasing energy absorption capability denote the cracking propagation are reduced significantly by adding fibres (Robins et al., 2002; Khaloo and Afshari, 2005; Altun et al., 2007 and Olivito and Zuccarello, 2010).

2.3.4 Mode of Failure

The mode of failure consists of shear failure, bending failure (flexural), cracking failure and deflection failure. The shear failure and flexural failure are focused here as the scope of study. Shear failure is characterized by large diagonal shear crack where the flexural failure is failed by means of diagonal tension (Matthys, 2000). The pictures below show the examples of shear failure and flexural failure of beam.

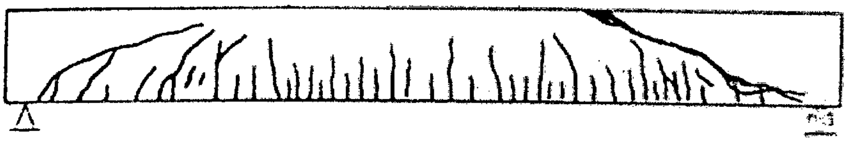

Figure **2.3**: Shear Failure of Beam (Adapted from Matthys, 2000)

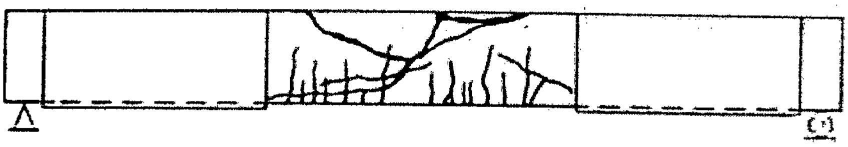

Figure 2.4: Flexural Failure of Beam (Adapted from Matthys, 2000)

The study of mode of failure of SFRC members allow the examination of the capability of steel fibres in increasing the shear strength of concrete. Normally, the shear resistant is contributed by the stirrups in the members. However, the stirrups are usually leading to the problem of steel congestion especially at the beam-column joint sections. The steel congestion may causes the segregation of concrete and affecting the strength of members strongly. Many investigations concluded that the adding of steel fibres are improving the shear strength of members significantly (Swamy and Bahia, 1985; Sharma, 1986; Oh et al., 1998; Cho and Kim, 2003 and Campione et al., 2006). Campione et al. (2006) observed that the shear resistant of the members were increased by the better bond conditions arisen by fibres. Investigations also found that the reduction of shear deformations at all stages of loading had increased as fibre content increased. Figure 2.4 shows the mode of