International RILEM Workshop on High Performance Fiber Reinforced
Cementitious Composites (HPFRCC) in Structural Applications
Honolulu, Hawai'i, 23-26 May 2005

TASK GROUP D – HPFRCC DESIGN ASSUMPTIONS CONCLUSIONS

Victor C. Li[1] and Keitetsu Rokugo[2]

(1) University of Michigan, Ann Arbor, Michigan, USA
(2) Gifu University, Gifu, Japan

Abstract

This article is a summary of the discussions and conclusions of Task Group (TG) D on Design Assumptions for HPFRCC, one of several task groups in the HPFRCC Workshop held in Hawaii, May 23-26, 2005.

1. INTRODUCTION

This article is a summary of the discussions and conclusions of Task Group (TG) D on Design Assumptions for HPFRCC, one of several task groups in the HPFRCC Workshop held in Hawaii, May 23-26, 2005.

2. DUAL DIRVERS OF HPFRCC FOR INDUSTRIAL ADOPTION

It is recognized that current structural design codes, e.g. ACI 318 has been specifically written for concrete. Structural designers who wish to adopt materials like HPFRCC with tensile strain-hardening behavior have little to rely on. While HPFRCC designs based on the current design code are likely conservative, it is desired to fully utilize the unique behavior of HPFRCC. One approach would be to provide specific provisions in a future version of the design code which adapts the code to recognize the influence of HPFRCC on structural response. Code bodies have expressed the desire to consider specific recommendations for modifications of the current design code in order to incorporate HPFRCC. An open invitation for recommendations has been extended to the materials community. Along this line, it is helpful to identify specific sections of the current code which require modifications when concrete is replaced by HPFRCC. It is understood that code bodies will want substantial documentations of real world performance and laboratory testing prior to code revisions.

In addition to recommendations resulting from past and planned research, the use of specific applications of HPFRCC in full scale structures may be used to serve as "application locomotives." Development of design guidelines, material specifications, and testing methods for commercially interesting applications is helpful to enhance acceptance of the use of HPFRCC for that application. These findings can then be generalized to broader application classes. This approach foregoes the limitations of current design codes, and provides substance for future code revisions. At the time of this writing, there are at least six existing or planned full-scale applications of HPFRCC which may serve this purpose. This number will likely grow in the coming years. RILEM TC HFC is collecting documentation of such full-scale applications, and plans to publish a Case Book on the same, perhaps adopting the style used by business educators for training of future managers. It is imagined that for each case, the following will be documented:

a. General background surrounding the specific application, including initial motivation behind the use of HPFRCC material
b. Performance target of the structure
c. Required property of HPFRCC
d. HPFRCC material specification
e. Structural design guideline
f. Execution
g. "Long term" performance
h. Conclusions

Further, the development of separate performance based design codes for HPFRCC may be advantageous, rather than simply broadening of the current design codes written for concrete. Performance based design code for HPFRCC will emphasize the ductility of the material as opposed to compressive strength typically, which is used to characterize concrete within current design codes. This approach may require checking strains in structural design. Performance based codes may also provide opportunities to design using an integrated structures and materials approach.

For broad adoption of HPFRCC in structural applications, it is expected that the following information is needed in the minimum:

a. Idealized material constitutive behavior, and
b. Simplified design assumptions and procedures

These two points form the foci of discussions in Task Group D.

3. TENSILE STRAIN-STRESS CURVE

The tensile stress-strain curve, with an extensive strain-hardening response, is the most unique characteristic of HPFRCC. For ultimate limit state (ULS) design, the full tensile strain capacity may be used. For service limit state (SLS) design, however, it may be necessary to limit the strain to ε_{tu} (ultimate tensile strain), corresponding to a maximum allowable crack crack width of w_{max} (Figure 1). This crack width must be determined based on durability considerations of the HPFRCC for the given environmental exposure. It may be assumed that when strained in tension beyond ε_{tu}, the HPFRCC may fail as the crack width increases beyond $w_{max.}$ Failure may mean a loss of tensile strain capacity, or in some other form. This consideration is based on the assumption that the large crack width will expose the matrix, fiber and interface to the environment which may alter the micromechanical properties, resulting in a change in composite load response. Apart from durability concern, SLS design may also impose limit on allowable ε_{tu} associated with excessive deflection.

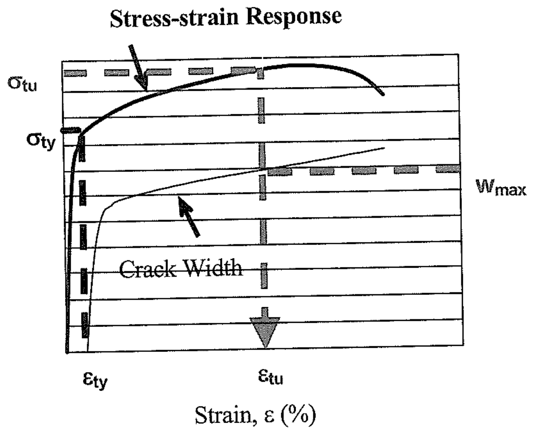

Figure 1. Cut-off of Strain Capacity by w_{max} for SLS Consideration

The idealization of the tensile stress-strain curve may be carried out in two levels (Figure 2). Level I adopts a simple linear elastic – perfectly plastic behavior. Level II allows for strain-hardening with a linear hardening response, with the possibility of accounting for a linear softening branch as well. In general, Level I is expected to lead to a conservative design, due to the excess load-carrying capacity beyond the idealized material behavior. However, in special circumstances which rely heavily upon a plastic response, strain-hardening of the material may delay or upset the intended structural performance, and lead to non-conservative designs. In this case, a design based upon the Level II material idealization would be more appropriate.

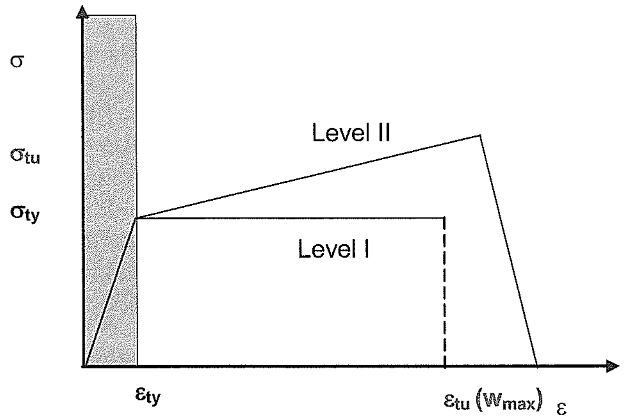

Figure 2: Level I and Level II Idealized Tensile Stress-Strain Relation

Because of material variability, the parameters (3 in the case of Level I) will need to be established on a probabilistic basis. This includes the parameter w_{max}. Proper resistance factor calibration should be applied.

A complete idealized stress-strain curve for both tension and compression is illustrated in Figure 3. Idealization in tension has been discussed above. Idealization in compression may follow that of normal concrete by employing the Witney stress block. While the compressive behavior of HPFRCC may not be significantly different from that of normal concrete, it is known that for some HPFRCCs (e.g. ECC), the compressive strain capacity can be as much as 30-50% higher, and the post-peak softening branch can be more gentle. These features may necessitate the recalibration of the values of ε_{cu}, β_1, and the relationship between σ_{cu} and f_c'.

In addition, the relation between Young's Modulus, E, and compressive strength, f_c', is expected to be different from that for normal concrete. There is also a need to verify any difference between the Young's modulus in tension and in compression.

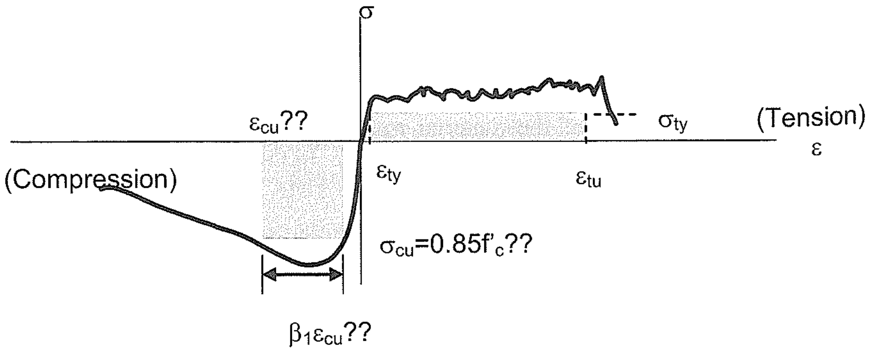

Figure 3: Idealized Stress-Strain Curve in Tension and Compression

4. BASIC DESIGN ASSUMPTIONS FOR REINFORCED FLEXURAL MEMBERS

The basic design assumptions typically used in structural design codes, e.g. ACI 318-2 and 318-02R (Section 10.2.1) includes the following:

a. Plane sections remain plane
b. Linear strain distribution across section
c. Compatible strain between concrete and reinforcements

These assumptions remain valid for HPFRCC. The third assumption concerning compatibility between concrete deformation and steel reinforcement deformation is perhaps even more valid for HPFRCC than for normal concrete since it is expected that the elastically unloading cracks in concrete will cause severe tensile stress locally at the reinforcement, resulting in high interfacial shear and therefore bond splitting. Thus the third assumption may be valid in R/C structures only prior to concrete cracking, while this same assumption is expected to hold true even when both steel and HPFRCC undergoes inelastic strain-hardening deformation.

With regard to reinforcement considerations, increasingly large amounts of data have been accumulated showing that shear reinforcement may be reduced or even totally eliminated in HPFRCC members. Also, in light of the self control of crack widths in some HPFRCCs, there may be no need for steel reinforcement placed mainly for controlling cracks.

5.0 RESEARCH NEEDS

A number of research needs were suggested during the discussion and concluding sessions in relation to Task Group D's focus. These are outlined below, without prioritization:

a. Load Resistance Factor Design (LRFD)
    1. RF calibration
    2. Time dependency of material parameters
c. SLS and ULS design
d. Moving from strength-based to strain-based design, checks on max strain and crack width
e. Classification of different versions of HPFRCC?
    a. High strength, low ductility
    b. Low strength, high ductility
f. Compression idealization
g. Young's modulus
h. Crack width development as function of strain
i. Nature of cracks in HPFRCC
j. w_{max} determination under combined environment and mechanical load
    a. environmental exposure

    b. specimen geometry
    c. magnitude and type of preloading
k. Thermal stress prediction in mass structures
l. Reinforcement considerations
    a. Development length
    b. Minimum clear cover
m. 3-D numerical code development for structural simulation
n. Full scale tests
o. Marine applications of HPFRCC

6.0 CONCLUSION

The discussions in this TG overlap significantly with those in other TGs, especially TG A on Standards for Materials and Testing and TG B on Durability. These TGs share common interests in the idealization of the tensile stress-strain response, and its connection to SLS and ULS design in structural use. Much research remains to be undertaken, despite the significant number of advances in HPFRCC materials and applications in recent years. The pathway toward development of structural design codes, along with the type of design code, remain topics deserving focused attention. However, it is hoped that the discussions and conclusions drawn from this TG provide meaningful input to the planning and efforts of the three subcommittees on Testing, Durability and Design under the umbrella of RILEM TC HFC.

7.0 ACKNOWLEDGEMENT

M. Lepech took detailed notes of the discussion and conclusion sessions of this TG which greatly aided in putting together this summary.