# 繊維補強コンクリート部材の釣合鉄筋比
# Balanced Reinforcement Ratio for FRP Reinforced Concrete Members

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## 1　INTRODUCTION

Advanced Fiber Reinforced Polymer (FRP) composites have the potential to become a prominent construction material in the twenty-first century. In the past decade, the use of advanced composites as reinforcement for concrete structures, as substitute for steel, has emerged as one of the most promising new technologies in construction. FRP composites, unlike steel, are supposed not to corrode. Hence, when used in concrete structures, they can potentially eliminate durability problems, which lead to structural degradation and consequently costly repairs and loss of use. Especially in cases where the likelihood of reinforcement corrosion is significant, opting for FRP bars can prove to be cost-effective by extending the life span of the structure. FRP bars are also lighter than ordinary steel reinforcement, magnetically and electrically transparent and have significantly higher ultimate tensile strength.

Before the adoption of any new reinforcing material in construction, extensive research is required to enable engineers to understand its fundamental behavior and differences with conventional reinforcement. Traditionally, concrete members with steel reinforcement are designed for tension failure to take advantage of the elastic-plastic behavior of steel. Unlike steel, FRP reinforcement has a linear stress-strain behavior until failure. This vital difference has attracted many researchers to answer the question, which is better mode for FRP reinforced concrete members, tension or compression failure mode? There have been many published experimental results about the behavior of concrete elements using FRP reinforcing materials under different reinforcement and load configurations. For example, in research regarding the behavior of FRP reinforced concrete beams, many studies can be found under both tension and compression failure modes, while studies on balanced strain failure condition (which represents a limiting value in demarcating tension and compression failure modes) are still rare, and therefore more data are needed.

## 2　BALANCED FAILURE MODE FOR FRP CONCRETE MEMBERS

Balanced failure condition is defined as the idealized situation, where strains in concrete and FRP bars simultaneously reach their predefined limiting values, that is, $\varepsilon'_{cu}\,(=0.0035)$ and $\varepsilon_{fu}\,(=f_{fu}/E_f)$ in concrete and FRP, respectively. Balanced failure condition is very difficult to achieve in reality; however, it represents a limiting value in demarcating the tension and compression failure modes. Balanced reinforcement ratio for FRP reinforced sections can be obtained by modifying equation (C6.2.3) in JSCE Standards, given for steel reinforced sections, using the material properties of FRP and Eq. (1) is obtained for rectangular beams by force equilibrium and strain compatibility. For a tension failure $p < p_b$ and for a compression failure $p > p_b$,

$$p_b = \alpha \frac{\varepsilon'_{cu}}{\varepsilon'_{cu} + f_{fu}/E_f} * \frac{f'_c}{f_{fu}} \qquad \textbf{(1)}$$

Where $f'_c$ is the compressive strength of concrete, $f_{fu}$ is the ultimate tensile strength of FRP, $E_f$ is the tensile modulus of elasticity of FRP and $\alpha$ = 0.68 (in case $f'_{ck} \le 50N/mm^2$).

## 3　VERIFICATION OF THE SUGGESTED FORMULA

At the moment, in the absence of codified design guidelines, research and development engineers need to validate any design assumptions either by testing or by numerical analysis, which is much cheaper than testing. Finite Element Analysis (FEA) is one of the most powerful tools available for engineers to help solve complex structural problems. The use of non-linear FEA represents a major technological achievement in the design of reinforced concrete structures. Due to advances in computer software and hardware technology, simulation of real structural behavior is available. It is possible to subject a virtual model of a civil engineering structure to design conditions and investigate its response. During this study, it was available to carry out the analysis using the commercial software ATENA, which is developed for non-linear FEA of concrete structures.

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At first it was of great importance to examine the accuracy of the program and be sure about the reliability of the results that it gives. Six FRP concrete beams, with already published results, were considered in order to examine how the computer program ATENA predict load-midspan deflection curve, crack pattern and failure modes of the tested beams. Beams were selected with different geometries, different concrete properties, different reinforcement properties and reinforcement ratios, as in [1], [2], [3]. Summary of the comparison between analytical and experimental results is shown in table 1.

**Table 1 Comparison between analytical and experimental results**

| Beam | Max. Load ($KN$) | | | Crack width ($mm$) | | | Failure mode | |
|---|---|---|---|---|---|---|---|---|
| | Ana. | Exp. | Ana. /Exp. | Ana. | Exp. | Ana. /Exp. | Ana. | Exp. |
| GB2 | 50.0 | 52.9 | 95% | | Not available | Not available | S | S |
| GB10 | 94.4 | 103.0 | 92% | | | | C | C |
| COMP-25 | 60.8 | 69.0 | 88% | | | | C | C |
| GB1-1 | 51.2 | 50.0 | 102% | 2.92 | 3.3 | 88% | T | C |
| GB2-2 | 54.7 | 53.6 | 102% | 2.57 | 2.2 | 117% | C | C |
| GB3-1 | 55.9 | 59.2 | 94% | 1.77 | 1.8 | 98% | C | C |

**Note:** S= Shear failure, C= Flexural compression failure and T= Tension failure.

After confirming accuracy and reliability of results from ATENA, the second step in the study is to verify the suggested formula in equation (1). Among the six beams studied earlier, three beams were selected. Geometry and properties of concrete and FRP reinforcement were kept the same without any change for all beams. Only reinforcement ratios were modified to produce balanced failure condition, using Eq. (1). It was observed at load step before failure, as shown in Fig. 1, that maximum compressive strains in concrete were 0.001, 0.003, 0.003 (failure strain 0.0035) while maximum tensile strains in FRP bars were 0.019, 0.018, 0.016 (failure strains 0.022, 0.02, 0.017) for beams GB Balance-1, 2 and 3 respectively, which means beams are very near to failure. At next load step (failure), beams failed where strains in concrete and FRP exceeded failure strains. Failure of concrete and FRP at the same time means balanced failure condition.

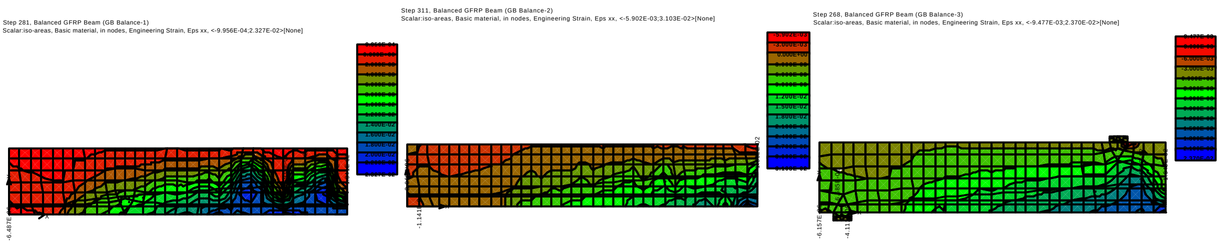

**Fig. 1 Beams GB Balance-1, 2, 3 at load step before failure (half sections)**

## 4 CONCLUSIONS

1. As a result of the comparison between analytical and experimental results in this study, it is evident that computer program ATENA can produce accurate predictions for the behavior of FRP reinforced concrete members (like beam) in both ultimate and serviceability limit states.
2. Based on results from numerical analysis carried out in this study, the formula presented for balanced strain reinforcement ratio is applicable for rectangular beams reinforced with FRP reinforcement.
3. Based on experience with analysis carried out for this study, the main problem in the analysis of FRP reinforced concrete members is the mechanical characteristics of concrete not FRP, which is linear elastic until failure, unlike steel. Hence, getting accurate results depend mainly on modeling of the concrete reflecting its actual properties.

## References


[1] Duranovic, Pilakoutas and Waldron, 1997, "Tests on Concrete Beams Reinforced with Glass Fiber Reinforced Plastic Bars", *Non-Metalic (FRP) Reinforcement for Concrete Structures*, Proceedings of Third International Symposium, V. 2, pp. 479-486.

[2] ALMusallam, AL-Salloum, ALSayed and Amjad, 1997, "Behavior of Concrete Beams Doubly Reinforced by FRP Bars", *Non-Metalic (FRP) Reinforcement for Concrete Structures*, Proceedings of Third International Symposium, V. 2, pp. 471-478.

[3] Toutanji and Saafi, 2000, "Flexural Behavior of Concrete Beams Reinforced with Glass Fiber-Reinforced Polymer (GFRP) Bars", *ACI Structural Journal*, V. 97, No. 5, September-October 2000, pp. 712-719.