A Comparison of Flexural Strength of Reinforced Concrete Beams by Different Design Codes

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Abstract—Design building codes are primary book for structural design engineers to calculate flexural strength. In the design building codes, concrete has important parts. Those are rectangular stress block model and compression strain. This paper evaluates flexural strength of the reinforced concrete beams using six different design approaches like ACI 318-14, AS3600-2009, CAN-A23.3-04, fib Model Code 2010, JSCE 2010 and NZS 3101:2006. Thirty-five test of reinforced concrete beam specimens in this database were tested under four-point monotonic loading. Compressive strength of the concrete is in the range of 18 - 55 MPa and shear span-to-depth ratio is in the range 3 - 5. Based on limited database, the rectangular stress block and compressive strain proposed by fib Model Code 2010 resulted in a mean ratio of the predicted nominal flexural strengths to measure flexural strengths close to 1.0 with a small standard deviation and coefficient of variation. In other hand, the model proposed by CAN-A23.3-04 provides the most conservative estimation.

Keywords—flexural, strength, beams, stress, strain

I. INTRODUCTION

Reinforced concrete is one of the most popular building materials used in the construction. Many structures and infrastructures use reinforced concrete as the main material for low-rise buildings, high-rise buildings, bridges, high-ways and U-ditch. According to the database from the Council on Tall Buildings and Urban Habit (CTBUH) [1], as presented in Fig. 1 showed the percentages of different construction materials that have been used in the world for building with more than 150 m height in two different years. There are six types of construction materials shown in Figure 1, including steel, concrete, composite, precast, concrete/steel and steel/concrete. Based on definition given by CTBUH, concrete refers to building whose the main structural elements are constructed by reinforced concrete (RC). It can be noted that the percentage of RC structures has increased from 39% to 68% in the past two decades.

![Fig. 1. Percentages of different structural materials used in building with more than 150 m height [1]](image1)

Design codes are primary book for structural design engineers to estimates flexural strength. One of the parts of the flexural strength is concrete strength. In the design codes, concrete has important parts, namely compression zone stress block model and compression strain. Different country has different equation to calculate flexural capacity. The objectives of this research are to review the building codes and compare the flexural strength in six different building codes: ACI318-14 [2], AS3600-2009 [3], CAN-A23.3-04 [4], fib Model Code 2010 [5], JSCE 2010 [6], and NZS 3101:2006 [7]. The motivation of this paper is not only to find the closest result based on different design codes, but also the ratio (experiment vs. design) for each test specimen with the results of conservative beam level is flexural strength for each code which can be seen clearly. The direction of this research is to suggest flexural strength capacity equation for normal-strength concrete to be use by engineers in practice to design reinforced concrete members with compressive strength less than 55 MPa, especially for Indonesian building code.

II. LITERATURE REVIEW

The concept of using the equivalent rectangular stress distribution was first suggested by Emperger [8] and then modified by Whitney [9] for application to ultimate strength design and later experimentally verified by Hognestad et al. [10] and Mattock et al. [11]. The ultimate flexural strength is assumed to occur at a particular value of extreme fiber concrete strain, $\varepsilon_{cu}$. The rectangular stress block (illustrated in Fig. 2) is defined by two parameters, $\alpha_1$ is ratio between the stress of the rectangular block and the maximum stress and $\beta_1$ is factor related to the depth of equivalent rectangular compressive stress block to neutral axis depth. Ultimate concrete compressive strength is another significant variable in the ultimate strength design. Mattock et al. [11] concluded that the value of 0.003 is a reasonably conservative value for ultimate strain of concrete. Some design codes (NZS 3101:2016, ACI318-14 and AS3600-2009) accepted this value.

![Fig. 2. Equivalent Rectangular Stress Block](image2)
Table I summarizes various recommendations for the stress block parameters ($\alpha$ and $\beta$) and $\epsilon_{cu}$ from various international design building codes.

| Building Code | $\alpha$ ($f_c'$ in MPa) | $\beta$ ($f_t'$ in MPa) | $\epsilon_{cu}$ |
|---------------|--------------------------|------------------------|----------------|
| ACI318-14 [2] | 0.85                     | 0.85-0.05 ($f_c'/28$)  | 0.0030         |
| AS3600-2009 [3] | 1.0-0.003$\epsilon'$ | 0.67 - $\alpha$ ≤ 0.85 | 1.05-0.007$\epsilon'$ | 0.67 ≤ $\beta$ ≤ 0.85 | 0.0030         |
| CAN-22.3-04 [4] | 0.85                     | 0.0015$\epsilon'$ ≥ 0.67 | 0.97-0.0025$\epsilon'$ ≥ 0.67 | 0.0035         |
| CEB Model Code 2010 [5] | 1.00$\epsilon'$ ≤ 50 | 0.8, $\epsilon'$ ≤ 50 | 0.8-0.8$\epsilon'$ ≤ 50 | 50 ≤ $\epsilon'$ ≤ 90 | 0.0035, $f'_t$ ≤ 50 | 0.0026+$\frac{90 - \epsilon'}{100}$ |
| JSCE 2010 [6] | 1-0.03$\epsilon'$ ≤ 0.85 | 0.52 - 80$\epsilon_{cu}$ | 0.0035 $\frac{155 - \epsilon'}{500}$ | 0.0025 ≤ $\epsilon_{cu}$ ≤ 0.0035         |
| NZS 3101:2006 [7] | 0.85, $\epsilon'$ ≤ 55 | 0.85, $\epsilon'$ ≤ 55 | 0.85-0.004$\epsilon'$ ≤ 55 | ≥ 0.75         | 0.85-0.008$\epsilon'$ ≤ 55 | 0.8 ≤ $\epsilon'$ ≤ 30 | ≥ 0.65         | 0.003         |

Metally [12] evaluated 53 singly-reinforced concrete beams tested by Pam et al. [13], Bernardo and Lopes [14], Sarkar et al. [15] and Ashour [16]. These beams have been compared to the predictions by seven different codes. Based on 53 beam specimens, CEB/FIP Model MC 90 code [17] presents the best prediction with the smallest scatter.

### III. METHODOLOGY

A total of 35 reinforced concrete beam specimens with rectangular cross section were collected, using conventional-strength concrete and had two layers of longitudinal reinforcement, compression and tension longitudinal reinforcement. All specimens were tested under a four-point loading experimental setup, as shown in Fig. 3. The two concentrated loads were applied symmetrically from the midspan.

![Beam specimen](image)

Fig. 3. Typical experimental setup

The range of material properties for the collected beam specimens are listed as follows: shear span-depth ratio ($a/d$): 3.00 – 4.96; concrete cylinder strength ($f_c'$): 18 – 55 MPa; tension longitudinal reinforcement yield strength ($f_t'$): 377 – 540 MPa; transverse reinforcement yield strength ($f_y$): 250 – 541 MPa; minimum diameter of transverse reinforcement: D10; and $\nu_{scl}\alpha/M_{scl} ≥ 1$, where $\nu_{scl}$ is specimen nominal shear strength used testing material properties based on ACI318-14, $M_{scl}$ is specimen nominal moment capacity using tested material properties based on ACI318-14, $P$ is load, $a$ is shear span and $d$ is effective depth. Material properties to determine the yield of flexural strength using elastic-plastic behavior for steel. Detail of beam specimen is presented in Table II.

### IV. RESULTS AND ANALYSIS

In this section, the $V_{exp}/V_{calc}$ ratio of 35 test results of reinforced concrete beams with normal strength concrete are presented and compared with the predictions of the above code equations. Table III shows the value of the ratio between experimental and theoretical results.
As seen in Table III, based on the calculation of all design building codes, there are only two papers, Slijkerman et al. [41] and Nordin and Talisjen [42], that have $V_{exp}/V_{nom}<1.0$, but still close to 1.0. It means the theoretical flexural strength is that calculated by all design codes are smaller than the experimental flexural strength.

A resume analysis of experimental strength versus nominal flexural strength is presented in Table IV. As seen from Table IV, nominal flexural strength model by fib Model Code 2010, $V_{nom,fb}$ provides the closest estimation for the ratio of $V_{exp}/V_{nom,fb}$.

Table IV shows the best results of the design of concrete structure, fib Model Code 2010 gives the smallest standard deviation and coefficient of variations. Nominal flexural strength model by CAN-23.3, 2006 exhibit the conservative estimation for 33 beam specimens.

V. CONCLUSION AND RECOMMENDATION

The following conclusions are drawn based on database and analytical results presented in this research:

1) fib Model Code 2010 provides the closest estimation for the ratio of $V_{exp}/V_{nom}$, with smallest standard deviation and coefficient of variations that is 0.079 and 0.073, respectively.

2) Among flexural strength models evaluated in this research, the model proposed by Canadian code exhibit the most conservative estimation for 32 test of RC beam specimens.

3) All of the design building codes gave more than 85% under-prediction of the RC beam test specimens.

This study is based on limited test results and future studies are needed to verify the findings.

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