Evaluation of Shear-Critical Reinforced Concrete Beam Blended with Fly Ash

M Mooy¹, A Tambusay¹*, I Komara¹, W Sutrisno¹, Faimun¹, P Suprobo¹

¹Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia
*Corresponding author’s e-mail: asdam@its.ac.id

Abstract. Results of an experimental investigation on shear-critical responses of small-scale reinforced concrete beams fabricated with normal concrete (NC) and concrete blended with supplementary materials using Class F fly ash (SMFA) are presented. The beams were reinforced with adequate stirrups as per requirement specified in design specifications. The beams were tested using Ohno beam testing setup to induce direct shear mechanisms across the shear plane. It was also intended to evaluate the shear capacity of a disturbed region (D-region) where the flexural moment was negligible. It was found that all beams fail in brittle shear manner, showing a significant increase of shear forces with a subtle increase in beam deflection. It was also found that the use of adequate stirrups could cease the localised crack formation. In overall results, it was found that the use of Class F fly ash as cement replacement was applicable because the response did not differ significantly.

Keywords: shear, supplementary material, fly ash, Ohno shear beam, reinforced concrete beam

1. Introduction

Since extensive scale coal firing for electrical power plants generation began in the 1920s, many millions of tons of ash and related by-products have been generated. According to Ahmaruzzaman [1], the typical annual production of coal ash generated worldwide is estimated around 600 million tons, with fly ash content being about 500 million tons at 75-80 per cent of the total ash produced. This high number of fly ash production released by factories and electrical power plants is significant compared to its utilisation, making it characterised as waste materials [2]. Due to its minor use in construction materials unlike Portland cement clinker, the factories have been facing problems on its disposal where they must provide landfills and/or lagoons which eventually would cost them greatly.

Fly ash particles are considered to be enormously contaminating, due to their content of potentially toxic trace elements which condense from the flue gas [3]. Research on the potential utilisation of these by-products has environmental relevance, in addition to industrial interest. Over the last decades, the use of these wastes has focused on a mission to prevent an increasing toxic threat to the environment or to exploit its significance in creating a safer and greener infrastructure due to the replacement of cement clinker [4].

The chemical properties of fly ash are influenced to a great extent by the properties of burned coal and the techniques used for its handling and storage. The primary components found in coal fly ash are silica
(SiO$_2$), alumina (Al$_2$O$_3$), iron oxide (Fe$_2$O$_3$), and calcium (CaO), with varying amounts of carbon as per measurement using loss on ignition (LOI) [5]. The proportion of each compound, however, may vary to some extent depending on where the fly ash is generated. This is the underlying reason why fly ash is categorised into three different classes. According to the American Standard for Testing Materials (ASTM C618) [6], ash comprising more than 70 per cent SiO$_2$ + Al$_2$O$_3$ + Fe$_2$O$_3$ with low lime content are defined as Class F, while those with the same contents in a range between 50 to 70 per cent and with high lime are defined as Class C. Due to this discrepancy, a proportion of fly ash as supplementary material in concrete needs to be adjusted as it will affect the overall material response for example compressive strength. It is common to replace Portland cement with Class F fly ash by 15 to 25 per cent of the cement mass, whereas the replacement using Class C fly ash can be higher at up to 40 per cent [7].

As the environmental relevance becomes an interesting cause to utilise fly ash in concrete, there have been extensive reports published online with regard to the potential that has concerned the industrial uptake. Research related to the utilization of this by-product not only have focused on the confirmation of structural performance [8-9] but also to a greater extent, the work has covered in a varied range of its application such as durability performance [10-13] or the novel development of initiative materials (e.g. engineered cementitious composite) [14-16].

In this current work, the utilisation of fly ash is directed toward its application in a reinforced concrete beam. The beam is designated to be tested under four-point bending mimicking Ohno beam setup arrangement which was first introduced in 1957 [17], and the beam was designed to fail in shear on purpose. Ohno testing set up was adopted herein as the concept represents the state of direct shear-tension configured in such a way where the bending moment is equal to zero, giving a chance for a significant development of shear cracks along the shear plane to occur. The experimental work comprised of two reinforced concrete beams being tested and evaluated: one was made with normal concrete (NC), and the other made with concrete blended with fly ash as supplementary material (SMFA).

The assessment regarding the shear behaviour of these two beams was based upon the common problems in brittle shear failure which is sudden and without warning, in particular to the member having a disturbed region such as in thick sections and wide beams [18] or in ordinary beams weakened by tensile forces [19]. When a member is subjected to moment and shear, premature shear failure may occur in a structural member containing little or no shear forces. Given that, this paper reports an attempt to gain improved insights into the shear mechanism throughout the process of cracking in reinforced concrete beams.

## 2. Materials and Fabrication

### 2.1 Test specimen

A series of 10×20×200 cm$^3$ reinforced concrete beams made of normal concrete, normal concrete blended with supplementary materials and engineered cementitious composite (ECC) were fabricated and tested in the warehouse of PT. Wijaya Karya Beton in Pasuruan, but only the results of two beams failing in direct shear are presented herein. The first and the second beam, hereafter referred to as Beam NC and Beam SMFA respectively, had five longitudinal steel bars in which two served as compression bars and the other three as tension bars. These steel bars were tied up and confined with two-leg closed stirrups spacing 10 cm at each thereby giving 20 Nos of transverse reinforcements. Details of beam specimen are shown in Figure 1 with the cross-section of the beam and steel bar properties presented in Table 1 and Table 2.

The mix proportions used to produce Beam NC and SMFA are presented in Table 3. The concrete mix had a water-to-cement ratio (w/c) of 0.3 and used ordinary Portland cement Grade 42.5, referred to as CEM I 42.5 R-NA in DIN 1164 [20]. A summary of concrete compressive strength as per ASTM C39/C39M–14 [21] is summarised in Table 4.
The fabrication of beams and cylinders was done in a single batch each using a 150-litre pan mixer. During casting, fresh concrete was internally compacted using a vibrating poker to ensure no air bubbles were trapped inside the specimens. Immediately after the concrete pouring was done, the top surface was trowelled smooth and then covered with a plastic wrap. The specimens were removed from their moulds after 24 hours and then stored in a curing chamber until required for testing (normally 28 days after casting). During this curing period, all specimens were regularly wetted to ensure the availability of water hydration.

**Figure 1.** Details of beam geometry and test setup

**Table 1.** Details of the beam cross-section

| Width $b$ (mm) | Height $h$ (mm) | Effective depth $d$ (mm) | Length $L$ (mm) | Span $a$ (mm) | $a/d$ |
|----------------|----------------|--------------------------|-----------------|--------------|-------|
| 100            | 200            | 157                      | 2000            | 315          | 1.8   |
### Table 2. Tensile properties of reinforcing bars

| Diameter (mm) | Area (mm$^2$) | Yield strength $f_y$ (MPa) | Ultimate strength $f_u$ (MPa) | Elastic modulus $E_s$ (GPa) | Strain hardening $\varepsilon_{sh}$ (%) | Ultimate strain $\varepsilon_u$ (%) |
|--------------|---------------|---------------------------|-----------------------------|---------------------------|--------------------------------------|----------------------------------|
| 8            | 50.3          | 405                       | 551                         | 200                       | 1.1                                  | 15.8                             |
| 10           | 78.5          | 484                       | 618                         | 200                       | 1.4                                  | 10.3                             |

### Table 3. Summary of concrete mix

| Specimen    | CEM I (kg/m$^3$) | 10 mm (kg/m$^3$) | Fine (<3mm) (kg/m$^3$) | Class F Fly ash (kg/m$^3$) | HRWR (g/m$^3$) |
|-------------|------------------|-----------------|-------------------------|----------------------------|----------------|
| Beam NC     | 525              | 1054            | 764                     | -                          | 5.5            |
| Beam SMFA   | 470              | 1052            | 731                     | 80                         | 5.5            |

### Table 4. Summary of 28-day compressive strength obtained from 300 mm cylinders

| Beam | Mean (MPa) | Standard of Deviation, SD (MPa) | CoV |
|------|------------|----------------------------------|-----|
| NC   | 45.9       | 9.6                              | 21.1|
| SMFA | 53.1       | 7.6                              | 14.4|

### 2.2 Test setup and instrumentation

The test setup and instrumentation used in the test specimens are shown in Figure 1. Each beam was initially placed into a stiff loading frame and laid onto two roller supports over a span of 630 mm. The beam was subjected to two-point loads unsymmetrically at a length of 630 mm with an arrangement based upon Ohno beam setup to induce the direct shear mechanisms. At each point load and support, high strength steel bar with a diameter of 25 mm was used.

Loads in the form of pressure in 50 psi increments were applied using an automated hydraulic jack actuator reacting against the spreader beam. Given the area of pressure is 0.02 m$^2$, the pressure of 50 psi (344.5 kN/m$^2$) corresponds with the load of 6.89 kN. To obtain the deflection, the linear variable displacement transducer (LVDT) was positioned beneath the beam at the centre of supports. FLA 5-11 strain gauges were also attached permanently to a longitudinal steel bar and stirrup to evaluate whether or not the bars were yielded. These instruments were connected to Tokyo Sokki Data Logger TDS-630 to acquire data at a rate of 1 Hz. To ease the identification of crack location, the front surface of the beam was sprayed white and 5 cm square gridlines were prepared prior to testing. The development of cracks was marked at each increment using permanent markers with different colours. A static digital camera was also prepared and placed in front of beam surface for crack mapping purposes using the digital image correlation (DIC) technique (readers are referred to [19, 22]). However, the DIC results are yet presented herein.
3. Results and Discussion

3.1 Shear force-deflection relationship

Results from the testing of two Ohno shear beams plotted in the form of average shear force versus average deflection are shown in Figure 2. It is evident that the first responses of the beams are linear elastic, depicting a significant increase in shear force with a subtle increase in beam deflection. The minimal increase in the deflection can be associated with the fact that the beam serves as a deep member having a disturbed region (D-region). As of this case, the deflection was affected due to the ratio of the shear span over beam effective depth much less than 2.0 or the ratio of a clear span not exceeding four times the overall member depth. Accordingly, D-region member is also linked to the nonlinear distribution of concrete strain, causing the beam to act as a tied arch. It is also interesting to note that Beam NC exhibited somewhat lower initial stiffness than that of Beam SMFA.

When the shear force was continued until ~20 kN, the cracks were formed for the first time along the shear span. When the shear force increased, both responses started to deviate from linearity where the discernible changes in stiffness were visible. Furthermore, the new development of cracks was apparent which was followed by the propagation of previous cracks with the tips extending towards the support. The availability of adequate transverse reinforcement herein was proven to have played an important role in preventing the beam from losing its capacity. A number of newly developed inclined cracks also proved that the beam had adequate energy to withstand the forces. At this stage, Beam NC demonstrated higher stiffness degradation compared to Beam SMFA. Regardless, it is worth noting that the increase of beam deflection was still minimal.

As the load further increased, the shear force was still proportional to the deflection. The propagation of cracks became apparent with significant crack widening and crack sliding. Beam NC eventually failed in a brittle manner at a force of 115 kN due to sudden crushing near the point load and the support (see Figure 3(a)) which was marked by the sudden drop of load (see Figure 2). Despite no manifestation of

![Observed final crack patterns at failure](image)

Figure 2. Shear forces-deflection relationships
concrete crushing, the Beam SMFA also failed in shear at a force of 130 kN which was slightly higher than Beam NC (see Figure (3b)).

Overall, the results suggest that transverse bars have a role to play in increasing the shear strength as well as delaying the occurrence of brittle shear failure. The discrepancy of Beam NC and SMFA was also insignificant, which may have occurred due to different concrete strength. Considering all of the above, the results signified that the utilisation of fly ash as a supplementary material did not alter the behaviour in terms of structural performance.

![Magnification (a)](image1)

![Magnification (b)](image2)

Note: numbers shown in crack pattern are in psi (please refer to Section 2.2 for conversion)

**Figure 3.** Crack patterns observed after failure: (a) Beam NC and (b) Beam SMFA
3.2 Strain Gauge Readings

The foil strain gauge with a single element (FLA-5-11) was attached to one of the longitudinal tension (bottom) bars and positioned over the shear span parallel to the bar to measure the progression of strain distribution during the increase of load. Likewise, an identical type of strain gauge was also placed vertically on transverse reinforcement for a similar purpose. For reference in Figure 4, the longitudinal and transverse gauges for Beam NC were labelled SG-NC #1 and SG-NC #2 respectively while in Beam SMFA, the gauges were labelled SG-SMFA #1 and SG-SMFA #2 in respective order of longitudinal and transverse strain gauges.

With regard to the readings as shown in Figure 4(a) and Figure 4(b), it was noticeable that the steel bars did not yield even after the specimens had failed. It is also worth mentioning that the strain response remained constant throughout the course of loading, owing to the fact that there was no significant jump occurring during the loading steps. To this extent, the results hence confirmed that the strain distribution of concrete was significant which had been the case of D-region member.

3.3 Crack Width

Figure 5 and Figure 6 show the representation of crack widths of Beam NC and Beam SMFA measured by a digital microscope. It was found that most of the cracks transpired along the shear plane, both in Beam NC and Beam SMFA, were structural. The typical crack width as depicted in the figure is greater than the crack width limit specified in the codes which are normally 0.3 mm. Nevertheless, it is worth mentioning that although the crack width from both specimens were relatively similar, the Beam SMFA had smaller crack width than Beam NC did.
4. Conclusions
Shear failure is a brittle phenomenon in reinforced concrete structures, in particular to members having disturbed regions as to what was the case of this limited investigation. It is thus of profound consideration that the behaviour is addressed to prevent such failure in the future. From this current work, the following conclusions can be drawn.

1. This work attempted to study the applicability of fly ash for its usage in concrete structures. In this regard, the results demonstrated that the influence of fly ash in reinforced concrete structure was not much different from the normal concrete which emphasised its potential to decrease the use of cement clinker.

2. It was shown that the shear capacity of Beam SMFA was somewhat higher than Beam NC due to higher compression strength.

3. From the strain readings, it should be noted that both the gauge placed on longitudinal steel bar and stirrup experienced significant action. It can be seen that the magnitude of strain was far below the theoretical strain at yield point suggesting the reinforcing bars were not yet yielded.

4. The crack width found in Beam SMFA was slightly smaller than in Beam NC.

References
[1] Ahmaruzzaman M A review on the utilization of fly ash 2010 Prog. Energy Combust. Sci. 36 327–63.
[2] Gollakota A R K, Volli V and Shu C 2019 Progressive utilisation prospects of coal fly ash: A review Sci. Total Environ. 672 951–89.
[3] Chadwick M J, Highton N H, and Lindman N 1987 The environmental significance of trace elements from coal combustion and conversion processes Environ. Impacts Coal Min. Util. pp
171–217.

[4] Rashad A M A 2015 A brief on high-volume Class F fly ash as cement replacement – A guide for Civil Engineer Int. J. Sustain. Built Environ. 4 pp 278–306.

[5] Rocca S, Zomeren A Van, Costa G, Dijkstra J J, Comans R N J and Lombardi F 2013 Mechanisms contributing to the thermal analysis of waste incineration bottom ash and quantification of different carbon species Waste Manag. 33 373–81.

[6] ASTM C618-05 Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete 2005

[7] ACI 232.2R-96 Use of fly ash in concrete 2002

[8] Ammisi A K and Ragul 2018 Strength and durability of high volume fly ash in engineered cementitious composites Mater. Today Proc. 5 24050–8

[9] Langley W S, Carette G G and Malhotra V M 1992 Strength development and temperature rise in large concrete blocks containing high volumes of low-calcium (ASTM class F) fly ash ACI Mater. J. 89 362–8

[10] Bilodeau A and Mohan M V 2000 High-volume fly ash system: Concrete solution for sustainable development ACI Struct. J. 97 41–8

[11] Adak D, ASCE A M and Mandal S 2019 Strength and Durability Performance of Fly Ash – Based Process-Modified Geopolymer J. Mater. Civ. Eng. 31 9 040191741–8

[12] Nath P and Sarker P 2011 Effect of fly ash on the durability properties of high strength concrete Procedia Eng. 14 1149–56

[13] Yoon Y S, Won J P, Woo S K and Song Y C 2002 Enhanced durability performance of fly ash concrete for concrete-faced rockfill dam application Cem. Conc. Res. 32 pp 23–30

[14] Şahmaran M, Özbay E, Yücel H E, Lachemi M and Li V C 2011 Effect of fly ash and pva fiber on microstructural damage and residual properties of engineered cementitious composites exposed to high temperatures J. Mater. Civ. Eng. 23 1735–45

[15] Zhang J, Leung C K Y and Cheung Y N 2006 Flexural performance of layered ECC-concrete composite beam Compos. Sci. Technol. 66 1501–12

[16] Komara I, Tambusay A, Sutrisno W and Suprobo P 2019 Engineered cementitious composite as an innovative durable material: a review ARPN J. Eng. Appl. Sci. 14 4 822–33

[17] Li V C, Mishra D K, Naaman A E, Wight J K, LaFave J M, Wu H C and Inada Y 1994 On the shear behavior of engineered cementitious composites Adv. Cem. Based Mater. 1 142–9

[18] Collins M P, Bentz E C, Quach P T and Proestos G T 2015 The challenge of predicting the shear strength of very thick slabs ACI Str. J. 37 11 pp 29–37

[19] Tambusay A, Suryanto B and Suprobo P 2018 Visualization of shear cracks in a reinforced concrete beam using the digital image correlation Intr. J. Adv. Sci. Eng. Inf. Tech. 8 2 573-8

[20] DIN EN 197-1 Special cement composition and conformity evaluation 2000

[21] ASTM C39-C39M-14 Standard test method for compressive strength of cylindrical concrete specimens 2014

[22] Suryanto B, Tambusay A and Suprobo P 2017 Crack mapping on shear-critical reinforced concrete beams using an open source digital image correlation software Civ. Eng. Dimens. 19 2 93–8

Acknowledgement
The authors wish to acknowledge the financial support from the Ministry of Research, Technology and Higher Education of the Republic of Indonesia, the in-kind contributions and technical support from PT. Wijaya Karya Beton Tb. in Pasuruan, and from the Laboratory of Concrete and Building Materials at Institut Teknologi Sepuluh Nopember.