ABSTRACT
For concrete structural behavior analysis, the complete axial stress–strain curves in compression can be determined by using a closed-loop servo-controlled hydraulic testing machine. The applied loading as well as the axial deformation reading of the loaded concrete specimen is recorded from the built-in displacement transducers or externally installed transducers placed between the machine platens. However, the recorded axial strain in the ascending branch is not purely concrete deformations but includes some additional deformation because of machine flexibility and specimen’s end restraint. Strain gauges can be diametrically installed at the middle of specimen for a more precise deformation reading but additional costs are required for the gauges and data acquisition system. Moreover, the concrete stress–strain curve and ductility performance beyond its ultimate is difficult to be recorded without special strain measuring devices. Hence, a correction equation is needed to account for these effects to obtain the complete stress–strain curves for unconfined and confined concrete. In this paper, a total number of 84 unconfined and steel strapping tensioning techniques (SSTTs) confined high-strength concrete cylinders of compressive strength ranging from 62.48 MPa to 184.85 MPa were tested in compression in accordance with ASTM C39/C39M-11. The details for the testing setup, testing machine, strain measuring instruments, loading rate, loading patterns, etc. are described and at the same time a correction factor equation is proposed in this paper.

Keywords
Complete stress–strain relationship, uniaxial compression load test, correction factor derivation, high-strength concrete, steel strapping tensioning technique (SSTT)

Introduction
A complete stress–strain curve for unconfined and confined concrete is important for performance analysis and concrete structure design. It documents the overall response of the concrete structure from the
beginning to failure under action of loading. It is quite a challenge
to derivate the complete stress–strain curve under uniaxial com-
pression because of two reasons: machine-specimen interaction
and difficulty in measuring the actual concrete strains from the
concrete specimen, especially upon reaching the ultimate com-
pressive strength of the specimen.

Concrete’s stress–strain relationship consists of two branches –
an ascending and a descending branch. Ascending branch goes
up to its ultimate stress and then followed by a descending branch
until erratic deformation is observed or the compressive strength
of concrete drops more than 50 % of its respective ultimate comp-
ressive strength, indicating failure of concrete. Testing machine
with loading or deformation control can easily capture the as-
cending stress–strain deformation provided it measures the cen-
tral region of the specimen using either electrical resistance strain
gauges, or embedding steel bar to hold the transducers, or a com-
pressometer. Recording the descending branch of the curve is the
most difficult part of the experiment. Concrete starts to crack and
deforms beyond the ultimate strength and these will damage the
strain gauge or alter the contact point of the compressometer,
resulting in erratic measurement, which do not representing
the true deformation but false deformation. The accuracy of
stress–strain relationship becomes particularly significant when
dealing with high-strength concrete where high ductility is ex-
pected. Unconfined, high-strength concrete is relatively brittle
and possesses lower ductility. However, the ductility increased
when it is properly confined such as by fiber-reinforced polymer,
concrete-filled tube, composite jacket, steel strapping tensioning
technique, etc. [1–13]. Unless the compressive test is able to gen-
erate accurate and meaningful stress–strain curve, the ductility
profile cannot be fully utilized.

Machine–specimen interaction is an accumulation of strain
energy in the testing machine because of deformation of speci-
men and machine during the loading process. The energy is
stored in the machine until the specimen reaches its ultimate
capacity. The stored strain energy is then suddenly released
as the concrete specimen has become weaker beyond its ultimate
strength, leading to a sudden failure of the specimen. Such en-
ergy is relatively larger when dealing with high-strength con-
crete. Several solutions have been proposed to eliminate or
reduce the interaction issue, e.g., control strain pace at a very
low level to prevent sudden disintegration of the specimen
and machine, or use steel cylinder in parallel with concrete test
specimen to reduce the sudden release of strain energy from the
machine during the entire test [14–21]. Nevertheless, even if the
interaction problem was solved, the challenge in recording the
descending branch of the stress–strain curve beyond the ulti-
mate strength remains unsolved.

In addition, the whole surface of the confined concrete spec-
imens was pre-tensioned with steel straps (Fig. 1) in this study,
and it is impossible to install any strain gauge in the longitudinal
direction especially in the center region to measure the strain
level. Hence, to obtain an accurate, stable, and full stress–strain
relationship, the concrete deformation values recorded between
the machine platens during loading are generally used to compute the strain value in the stress–strain curve. Nevertheless, these calculated deformations are mixed with other unwanted strain values from the end-zone effect and residual deformation within the mechanical system of the machine. These values need to be isolated. In this paper, a correction factor is proposed to segregate those unwanted strain values so that more accurate stress–strain curves of unconfined and confined concrete can be obtained for the entire ascending and descending branches. Please note that the correction factor might vary depending on the type of testing machine, the method of specimen preparation, the loading pace and patterns, as well as the testing procedure.

Experimental Program

TEST SETUP AND STRAIN MEASURING INSTRUMENTATION

All of the compression tests were conducted using a TINIUS OLSEN Super “L” Universal Testing Machine, which has a capacity of 3 MN. Displacement-controlled loads were applied with a constant rate of 0.4 mm/min. The compression testing configuration is shown in Fig. 2.

The overall longitudinal axial deformations of the specimens were obtained using the three linear variable differential transducers (LVDTs) with gauge length of 50 mm, which were located at the machine platen. Another three LVDTs with a gauge length of 25 mm were attached to the center of the specimens with a longitudinal rig. The relative axial displacement was measure over the 100-mm height of the concrete specimens. The transverse deformations of the specimens were obtained using two separate LVDTs (gauge length of 25 mm) located at the center of the specimens, diametrically wrapped with steel ties around the concrete specimen. The overall concrete longitudinal strains were calculated from the average value from LVDT readings divided by the particular measured length.

The transverse deformations for concrete and steel strapping were obtained by using two sets of strain gauges (gauge length of 60 mm and 10 mm for concrete and steel strapping, respectively) installed at the center of the specimen in a diametrically opposed direction. Besides measurement values, visible observations such as crack pattern, buckling, and abnormal deformation were also carried out during the tests. The compressive strength of specimens was obtained in accordance to the testing procedures contained in ASTM C39/C39M-11 [1]. Figs. 3 and 4 show the schematic diagram in detail for all measuring instruments used in this study, for both unconfined and confined concrete specimens, respectively. The only difference in measuring instruments between the two was the strain gauges to measure the lateral deformation of steel straps for confined concrete specimen.

LOADING PATTERNS—UNIAXIAL MONOTONIC LOADING TEST

In this study, the concrete specimens were tested under uniaxial monotonic loading tests to obtain their particular complete stress–strain relationship. Pre-load compression tests up to 10% of the concrete’s compressive strength have been carried out before the actual compression load test to eliminate the possibility of end-zone error. The loading pattern for this load test is shown in Fig. 5. The tests were performed until the compressive strength
FIG. 3
Schematic diagram for unconfined specimen with its measuring instruments: (a) plan view, and (b) top view.

FIG. 4
Schematic diagram for confined specimen with its measuring instruments: (a) plan view, and (b) top view.
of loaded concrete specimens dropped by more than 50% of its ultimate compressive strength. In some cases, the tests were stopped once erratic deformation was observed. Normally, erratic deformation happened in the post-peak region. Because such deformation does not represent the aspect of stress–strain behavior, the results were not counted. Some examples of erratic deformation obtained during the load test are shown in Fig. 6.

Derivation of Complete Stress–Strain Curve

To minimize the machine–specimen interaction as well as the disturbance from cracking while at the same time recording both ascending and descending branches of complete stress–strain curves, deformation of the concrete specimen between the machine platens were used to measure the concrete strains. This type of concrete strain is generally more reliable in the post-peak level but it does not fully represent the true strains of the specimen. The measured strain values included the unwanted end-zone effects and machine flexibility as per Mansur et al. [14]. These effects depended on the type of machine used, the method of preparation of the concrete specimen, testing procedure, and type of strain measuring technique. A correction factor (Eq1) has been successfully proposed by Mansur et al. [14] to eliminate the unwanted effects for unconfined high-strength concrete with compressive strengths ranging from 50 to 130 MPa. It is also believed that there is a different correction factor for both unconfined and confined concrete specimens, where a confined concrete specimen is the main objective of this study.

FIG. 5 Loading pattern for uniaxial monotonic loading test.

FIG. 6 Examples of erratic deformation for loaded concrete specimen (a to f).
\[ a = \frac{229}{f_c} + 2.91 \]  

**TEST PROCEDURE FOR CORRECTION FACTOR**

As the investigation for correction factor for the compression testing machine is a part of the investigation of the stress–strain behavior of unconfined and confined high-strength concrete in this study, a total number of 84 unconfined and SSTT confined high-strength concretes in the standard cylinders with dimensions of 100 × 200 mm and 150 × 300 mm were compressively tested using a TINIUS OLSEN Super “L” Universal Testing Machine. The design compressive strength of the unconfined concrete specimens were in the range of 65 to 107 MPa, whereas the compressive strength and confining ratio for the confined concrete specimens ranged from 63 to 185 MPa and 0.12 to 0.41 MPa, respectively. It is worth mentioning that the effect of cyclical loading was not included in this study. The compression test only utilized uniaxial monotonic loading in the vertical direction.

**PRELIMINARY TEST RESULT AND THE NEED FOR CORRECTION**

The LVDT rig used in this study had a fixed gauge length of about 95 mm for both types of standard cylinders (see Fig. 7); hence, the strain deformations obtained might probably contain some end-zone effects of the concrete specimen. To check the validity of the LVDT rig, unconfined concrete specimens of compressive strength of about 65 MPa and 110 MPa were installed with two sets of strain gauges with a gauge length of 60 mm in longitudinal direction, LVDT rig, and LVDT between the machine platens and tested with the uniaxial monotonic loading test until failure (Fig. 7). The stress–strain relationships derived from these two sets of deformations are shown in Fig. 9 and Fig. 10.

The experimental results show that the two sets of deformations measured are almost identical up to the peak load level for both the strain gauges and LVDT holder rig. The gauge length and the type of measuring instruments used in this study do not have a significant influence on the deformations. Hence, it can be concluded that the deformation of concrete specimens at the middle region has no end-zone effect. Because of the difficulty of using a strain gauge in the longitudinal direction for SSTT-confined concrete specimens, it was therefore only the LVDT rig that was used to measure the actual deformation of the confined specimens. It should be noted that deformations obtained by strain gauges and LVDT rigs are only validated until the peak load level, where erratic deformations were significantly observed beyond the post-peak level after cracking began to occur.

To capture the descending branch of the stress–strain relationship of the concrete specimen, LVDTs that were placed between the machine platens (see Fig. 8) were used. The stress–strain relationship, recorded using the LVDTs between machine platens, has also been compared with the curves recorded by LVDT rig, as shown in Figs. 9 and 10. A significant difference exists between the two curves at all stress levels, whereby a constant difference in the gradient has been noticed. Hence, there is a relationship between the mentioned constant and concrete strength. This relationship is the so-called correction factor that needs to be implemented in
all of the stress–strain curves obtained by LVDT between machine platens.

**DERIVATION OF CORRECTION FACTOR**

Because there is a significant difference between the stress–strain curves obtained by the LVDT rig and LVDT in the middle of machine platens, a general factor was derived by Mansur et al. [14] in their paper using Eq 2. The correction factor is \( \alpha \) comprised of initial tangent moduli of the concrete specimen based on the stress–strain curves derived from the LVDT rig and LVDT between machine platens in this study, as shown in Fig. 11. The inclusion of the correction factor in the deformation measured by LVDT between machines platens will give the corrected deformation similar to those measured by LVDT rig or strain gauges.

The derivations for the correction factor are described below. Let \( \Delta_{LO1} \) = deformation measured by LVDT rig over its gauge length, \( L_{rig} \), \( \Delta_{LO2} \) = deformation measured by LVDT between machine platens over its gauge length, \( L_p \), \( \Delta_s \) = the deformation because of machine flexibility and end-zone effect. The general deformation follows that:

\[
\Delta_{LO2} = \Delta_{LO1} + \Delta_s \tag{3}
\]

Rearranging Eq 3,

\[
\Delta_s = \Delta_{LO2} - \Delta_{LO1} \tag{4}
\]

The common equation for initial tangent moduli and strain,

\[
E = \frac{\sigma}{\varepsilon} \tag{5}
\]

and

\[
\varepsilon = \frac{\Delta'}{L'} \tag{6}
\]

where:

- \( E \) = young modulus of concrete specimen,
- \( \sigma \) = stress applied,
- \( \varepsilon \) = strain deformation of concrete specimen,
- \( \Delta' \) = corresponding deformation measured by LVDT, and
- \( L' \) = gauge length of the corresponding measuring instrument.

By substituting Eq 6 to Eq 5, we get,

\[
E = \frac{\sigma}{\Delta/L} = \frac{\sigma L'}{\Delta} \tag{7}
\]
Rearranging Eq 7,
\[ \Delta_0 = \frac{\sigma L_0}{E} \] (8)

Substituting Eq 8 into Eq 4, for its corresponding deformations measured by both measuring instruments, we get:
\[ \Delta_a = \frac{\alpha}{E_{L02}} \left( \frac{\sigma}{E_{L02}} - \frac{\sigma}{E_{L01}} \right) L_p \] (9)

Assume that \( L_p \approx L_{rig} \) as the strain difference is negligible compared to the length of the gauge; hence, we get:
\[ \Delta_a = \frac{1}{C_{18}} \left( \frac{\sigma}{E_{L02}} - \frac{\sigma}{E_{L01}} \right) L_p \] (10)

Substitute Eq 10 into Eq 4 to replace the deformation \( \Delta_a \):
\[ \Delta_{LO2} = \Delta_{LO1} + \left( \frac{\sigma}{E_{L02}} - \frac{\sigma}{E_{L01}} \right) L_p \] (11)

By changing the deformation of concrete specimen to strain values, we get:
\[ \varepsilon_{LO1} = \varepsilon_{LO2} - \left( \frac{\sigma}{E_{L02}} - \frac{\sigma}{E_{L01}} \right) \] (12)

By substituting the parameters in the parentheses with the correction factor as described in Eq 2, we get:
\[ \varepsilon_{LO1} = \varepsilon_{LO2} - (\alpha) \sigma \] (13)

where:
- \( \varepsilon_{LO1} \) = the newly corrected concrete strain at any stress level of \( \sigma \), and
- \( \varepsilon_{LO2} \) = the corresponding strain measured by LVDT between machine platens,

and the quantity in the parentheses in Eq 12 is the correction factor (\( \alpha \)) used to revise the deformation from the machine platens. It is believe that concrete strength will have influence on the correction factor; hence, a correction factor relates to concrete strength, representing the correction factor proposed and described in the next section.

CORRECTION FACTOR

In an attempt to figure out a correction factor that can be generally used on the testing machine in Universiti Teknologi Malaysia so as to avoid the excessive use of the LVDT rig and to obtain both the ascending and descending branches of a concrete specimen without any erratic deformation, the correction factors obtained for each individual test are plotted against its corresponding compressive strength, as shown in Fig. 12. The curve indicates that the correction factor becomes smaller as the compressive strength of concrete increases. This might be because the small lateral dilation of higher strength concrete compared to the lower strength concrete at the same applied loading leads to smaller deformation between the platens on which the LVDTs are installed, and hence results in smaller correction factor. The scattering test results are acceptable because such differences are normal when dealing with concrete specimens with a high range of compressive strength. The best-fit curve for the range of concrete strength covered in this study can be expressed as in Eq 13, where the correction factor ranges from \( 4 \times 10^{-6} \text{MPa} \) to \( 11 \times 10^{-6} \text{MPa} \) for a variation of concrete strength from 60 MPa to 185 MPa:
\[ \alpha = 0.0002 f_c - 0.0946 f_c + 15.447 \] (14)

where:
\( \alpha \) = the correction factor that is only valid in the testing machine at the Faculty of Civil Engineering, Universiti Teknologi Malaysia, and
\( f_c \) = the compressive strength of corresponding concrete specimens based on either 100 × 200 mm cylinders or 150 × 300 mm cylinders, for both unconfined and confined concrete specimens.

In the same graph, the correction factor proposed by Mansur et al. is also included for comparison purposes. Mansur et al. investigates the correction factor for unconfined concrete specimens (standard concrete cylinders and concrete prisms) with compressive strength ranges from 50 MPa to 130 MPa, whereas the current study investigates the unconfined and confined concrete specimens (standard concrete cylinders) using SSTT confinement, with the compressive strength ranging from 60 MPa to 185 MPa. For a similar compressive strength, it is notified that the gradient of both curves are almost the same but the curve for current study is much higher than existing ones. Mansur et al.’s correction factor is mainly applicable to unconfined concrete only but the current proposed correction factor is feasible for both unconfined and confined concrete, exaggerating the application of...
the correction factor. However, the correction factor would vary depending on the type of testing machine, the method of specimen preparation, the loading pace, loading patterns, and the overall testing procedure.

Fig. 13 shows the stress–strain curve for an SSTT confined concrete that has been corrected by using the proposed correction factor $\alpha$, as derived above for the universal testing machine. It can be found that the unwanted extra deformation of LVDT between machine platens has been minimized and the corrected curve is closed to the true deformation of the concrete specimen. For the entire set of testing data that needed to be corrected in this study, it was concluded that the maximum deviation between the corrected curve and the actual curve was less than 10%. Such a disparity occurs because of the unexpected pre-matured minor cracking error and other non-linearity in the end-zone effect. Therefore, it can be concluded that the correction factor proposed in this study is feasible for the particular universal testing machine in which an actual stress–strain curve could be obtained by regulating the strain value obtained by the deformation of machine platens using the proposed correction factor. By doing so, both actual longitudinal and lateral deformation of any types of confined concrete could be investigated without the use of any strain gauges and compressometer. This can save a certain amount of the budget on strain-measuring devices.

Conclusions

In this study, a total of 84 unconfined and SSTT-confined high-strength concrete cylinders with compressive strengths ranging from 62.48 MPa to 184.85 MPa with dimensions 100 mm × 200 mm and 150 mm × 300 mm in diameter and height, respectively, were compressively tested with a prescribed strain-measuring method. The results demonstrated that, by using LVDT rigs fixed directly to the concrete specimen and LVDT placed between the machine platens, a correction factor to segregate the machine flexibility and end-zone effect can be determined. By applying the correction factor, a near-to-actual stress–strain curve of unconfined or confined concrete in compression can be obtained without relying on strain gauges or a compressometer. It should be noted that the above conclusions have been reached only in regard to the laboratory tests conducted on standard, scaled, high-strength concrete specimens at the Faculty of Civil Engineering, Universiti Teknologi Malaysia. Correction factors would vary depending on the type of testing machine, the method of specimen preparation, the loading pace, loading patterns, and the overall testing procedure.

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