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Time dependent strain development of early age concrete under step-by-step load history

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HIGHLIGHTS

- Strain developments of concrete under step-by-step load history were studied.
- The validity of superposition principle in calculating creep strain was discussed.
- Strain development is substantially affected by the loading age and stress amplitude.
- Axial shortening is overestimated with larger stress amplitude and shorter loading history.

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ABSTRACT

With the increasing height of high-rise buildings, adverse effects caused by differential axial shortening become significant. Most of the calculation methods that have been developed to analyze the axial shortening of high-rise buildings are based on a common assumption that creep is linearly proportional to stress and conforms to the superposition principle. However, this assumption is rarely verified when it is used to describe the time-dependent deformation development of early age concrete in construction process. This paper presents an experimental study to examine the validity of this assumption in this use. A step-by-step load was employed to approximately simulate the load history of axial components experienced in the construction process and the strain developments were monitored. A comparative analysis between test results and numerical simulations shows that, the strain development of early age concrete under a step-by-step load is substantially affected by the loading age and stress amplitude, which verifies that the assumption, on which previous methods are based, may lead to inaccurate prediction of strain development in axially loaded concrete components. The time-dependent strain is overestimated with the larger step-by-step stress amplitude and shorter loading history.

1. Introduction

Good water resisting property, workability and economy make concrete material the most widely used construction material during the past centuries. Nevertheless, some of its intrinsic characteristics can also result in adverse effects for constructions [1–3]. Concrete shrinkage and creep are old but important topics in structural design. Prediction of these phenomena is essential for evaluating the risk of concrete cracking and additional deflections [4–7]. Although numerous theoretical and experimental researches have been conducted in this area, they are still far from being fully understood [8]. It has been a great challenge for current prediction models to effectively predict shrinkage and creep with the increasing use of high performance concrete materials [9–12]. Furthermore, new serviceability problems induced by concrete shrinkage and creep arise when it comes to high-rise concrete structures, e.g., the cumulative shortening of axial components in high-rise buildings becomes significant and the influence of differential shortenings among axial components on structural performance has been observed in buildings over 100 m since 1960s [13–16]. These adverse effects can induce stress redistribution, cracks, sloping of beams and floors, extra moment resulted from axial load sidesway and even the normal service problems of elevator [17–19].

Axial shortening analysis has become an essential procedure for high-rise buildings during both design and construction stage. It is generally accepted that there are five factors controlling the differential axial shortening of high-rise buildings, i.e. construction sequence, load differences among axial components, shrinkage and creep of concrete, time-dependent variation of concrete elastic modulus and non-uniform deformation induced by temperature

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[20–21]. Some numerical methods have been proposed to quantify the differential axial shortening of high-rise buildings by considering these five controlling factors [21–22]. The shrinkage and creep of concrete have been taken into account in the construction process simulation for most high-rise buildings, including the Burj Khalifa Tower which is currently the tallest building in the world [23–25]. With the rapid development of engineering practices, compensation measures for weakening differential axial shortening have been developed and fully discussed [20,23–25]. While the original shortening of axial components can be reduced effectively by adjusting the reinforcement ratio, cross section area, concrete type and strength grade, the axial shortening compensation during construction process can help lessen the differential axial shortening as well [26–27].

In most previous research, people assume that creep is linearly proportional to stress and conforms to the superposition principle. However, this assumption is rarely experimentally verified when it is used to predict the time-dependent deformation development of early age concrete under construction load history. Gardner's test results show that the superposition principle of creep strain was not valid for concrete in a drying environment. For loading before drying and drying before loading conditions, the measured incremental creeps were underestimated 20% and 10%, respectively [28]. Brown et al. reported that the creep development of early age high strength concrete was obviously underestimated when the above-mentioned superposition principle was used to calculate the creep strain of concrete under increasing load history [29]. In this study, a step-by-step load was employed to simulate the loading history of axial components in high-rise buildings during construction process. The time-dependent deformations of early age concrete under such load history were measured and the validity of superposition principle in calculating creep strain was discussed.

2. Experimental investigation

2.1. Concrete mix design and specimens

Commercial concrete was used in the test with the mix proportions shown in Table 1. The raw materials used are Portland cement of type 42.5R, coarse aggregate with a maximal diameter of 10 mm, natural sand, tap water, fly ash and water reducing agent. As the effects of geometry and environmental conditions on concrete elastic, shrinkage and creep strain developments are significant, although the standard tests have different special requirements for geometry of concrete specimens and environmental conditions for elastic modulus, shrinkage and creep measurement, only one uniform size, i.e. 100 × 100 × 400 mm were used, and all environmental conditions were kept consistent for all deformation measurements. Twelve concrete specimens were cast and two of them were randomly selected to determine the concrete elastic modulus at the age of 28 days. They were first cured for 24 hours in the moulds and then moved to laboratory environment after being demoulded. Twelve 100 mm-cubic specimens were also prepared in a similar way to evaluate the development of compressive strength as shown in Table 2.

2.2. Testing device and method

The loading and monitoring devices are shown in Fig. 1. A screw jack with a maximum capacity of 500 kN was used to load the concrete specimens. The loading force was monitored by a pressure sensor under the screw jack. A vibrating wire strain gauge was fixed on the concrete specimen surface to measure the shrinkage and creep strain development. The designed loading scheme is shown in Table 3. Three loading cases were considered, i.e. zero load, constant load (100 kN), and step-by-step load. The zero load condition was used to measure the drying shrinkage development of concrete and the constant load condition was used to evaluate the creep development [30]. With regard to the step-by-step load case, it was used to simulate the loading history of axial components in high-rise buildings. For actual high-rise buildings, the construction sequence is usually among 3–10 days per floor and the load increment from upper floors is mainly composed by dead load (self-weight) and construction live load. Referring to the construction process of an actual high-rise building, the step-by-step loading case employs 6, 12, 18 kN as load increments and 5 days as loading time internal [31]. These axial components in high-rise buildings are subjected to many load increments during the construction process. Each axial component will experience instantaneous elastic shortening, subsequent long-term shrinkage and creep deformation after a step load is applied (see Fig. 2).

The detailed experimental procedure is as follows:

(1) All concrete specimens, including twelve prisms and twelve cubes, were cast at the same time. They were all first moist-cured in moulds for 24 hours. Then the prisms were cured in a room environment while cubes were still moist-cured until 28 days.
(2) Strain gauges, with 150 mm gauge length, were fixed on the surface of concrete prisms using the structural adhesive. They are located along the central-line of the concrete specimen and in line with the screw jack.
(3) Shrinkage strain readings began on the 3rd day after casting. For the constant loading case, a total 100 kN loading force was applied on the two concrete prisms at the 30th day. For the step-by-step loading case, the step loads (6, 12, 18 kN) were first applied on the sixth day and subsequently applied at an interval of 5 days. The loading force in the last step varies a bit as the sum of the loads in all steps is designed to be 100 kN. Also, the designed load in each step decreases due to the development of shrinkage and creep strain, especially in the constant loading case. Compensation load was applied when the applied load fell over 2% of its initial value.
(4) Relative humidity and temperature were recorded every day.

Table 1
Proportions of concrete mix (kg/m^3).

Cement	Water	Sand	Stone	Fly ash	Admixtures
480	164	743	937	50	15.5

Table 2
Cubic compressive strength of concrete at different curing times.

Specimens		Curing time (days)			
		1	3	7	28
Strength (MPa)	Group-1	12.6	18.8	24.8	38.1
	Group-2	12.7	19.5	25.1	36.4
	Group-3	12.7	21.6	24.1	39.5
	Average	12.7	20.0	24.7	38.0

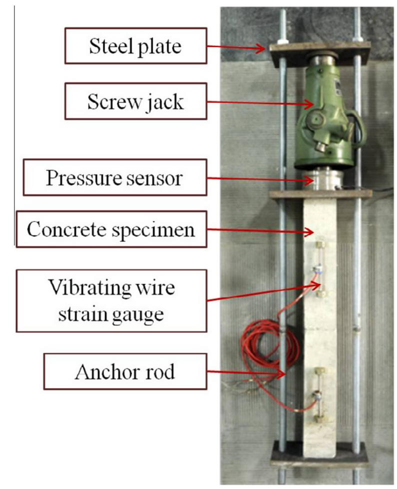

Fig. 1. Testing apparatus.

3. Results and discussion

The time-dependent deformation of a concrete member under compressive load consists 3 parts: the initial strain at loading (elastic strain), the shrinkage strain, and creep strain. According to the inducement, it can be further classified as stress dependent strain (initial strain at loading plus creep strain) and stress independent strain (shrinkage strain).