Research Article

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Research on nano-concrete-filled steel tubular columns with end plates after lateral impact

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Abstract: This paper presents thirteen square columns to study the behavior of nano-concrete-filled steel tubular columns with end plates after lateral impact. The failure modes of the square columns subjected to lateral impact damage or not subjected to lateral impact damage were compared. The lateral impact loading height, steel tubular thickness, and column height were set as the test parameters in these tests. The effects of test parameters on the ultimate capacity, initial stiffness, and ductility of columns are discussed in this paper. The bearing capacity of square columns is decreased because of the lateral impact loading which can also be concluded from the test results. And with the steel tube thickness increasing, the bearing capacity and initial stiffness of columns are increased and ductility has no obvious change. However, with the column height increasing, the bearing capacity and stiffness of columns are decreased and ductility is increased. Furthermore, the strain development of the columns under axial compressive loading is also discussed in the paper. The results indicated that the corner of the square column is more easily damaged under compressive loading. According to the test results, the calculated formula is proposed to predict the ultimate capacity of nano-concrete-filled steel tubular columns with end plates after lateral impact. The calculated results have a good agreement with the test results.

Keywords: nano-concrete, lateral impact, bearing capacity, initial stiffness, ductility

1 Introduction

Normal concrete is widely used in civil engineering structures because of ubiquitous availability and low cost. However, the low tensile strength, brittle behavior, and low strain capacity of normal concrete still exist. The application of nano-materials in many engineering fields has shown a new way to improve the performance of nominal concrete. Nano-SiO₂ is one of the most widely used supplements in nano-concrete because of its special surface and interface effects [1], which could greatly improve the property of concrete to achieve the high economic efficiency [2]. The application of nano-concrete in concrete structure was studied by the scholars [3], indicating that the application of nano-concrete promoted the social development. It is well-documented that the properties of concrete are improved [4] by combining the pozzolanic nano-materials such as SiO₂ with concrete [5]. For the building structure, the nano-concrete provided enough safety strength and was good for the development of building structure [6]. In this study, the nano-concrete is used to replace the nominal concrete in CFST columns. And the impact resistance of nano-concrete-filled steel tubular columns with end plates is investigated. The specimens with three test parameters of different impact height, steel tubular thickness, and column height are designed to study the behavior of nano-concrete-filled steel tubular columns with end plates. The lateral impact test and compression test are carried out. After tests, the effects of test parameters on the failure mode, ultimate capacity, initial stiffness, and ductility are discussed in the paper. The ultimate capacity of nano-concrete-filled steel tubular columns with end plates after lateral impact could be estimated by the calculated formula presented in this paper. The calculated results are compared with the test results, and the calculated results are in good agreement with the test results. It indicated that the calculated formula can provide a certain basis for the later application of nano-concrete. The process cycle is shown in graphical abstract.

In general, the previous studies focused on the behavior of material or the test of simple static load. For

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example, the scholars of Hosseinpourpia *et al.* [7] investigated behavior of nano-SiO₂ combined with sulfite fibers by testing the different mechanical properties of manufactured green composites. The result indicated that the properties of cement-based composites were enhanced because of addition of nano-SiO₂. The micro-structure of cement was studied by Sun *et al.* [8]. This study could serve as reference for the preparation of new three-layered cement-based wave absorbing boards. In addition, many scholars studied the effects of nano-SiO₂ particles on behavior of cement-based materials of mortar, cement, and concrete. The scholars of Senff *et al.* [9] studied the effect of amorphous nano-SiO₂ on fresh state behavior by the methods of adding the amorphous nano-SiO₂ in cement pastes and mortars. The result indicated that nano-SiO₂ modified the characteristics of fresh mortars. Otherwise, the effect of partial replacement of ordinary Portland cement (OPC) by various mineral additives in the screed mixtures and the freeze–thaw resistance of cement screed were investigated by Reiterman *et al.* [10]. Scholars of Pourjavadi *et al.* [11] studied the behavior of superabsorbent polymers in cement-based composites incorporating colloidal silica nanoparticles. The scholars of Said *et al.* [12] investigated the effect of nano-SiO₂ on concrete incorporating ordinary cement and ordinary cement + class F fly ash. The result indicated that the behavior of mixtures incorporating nano-SiO₂ was significantly improved.

However, the impact resistance of nano-concrete-filled steel tubular columns with end plates is not understood well. Thus, it is necessary to carry out the impact test to study the behavior of nano-concrete-filled steel tubular columns with end plates after lateral impact. The result of this study can provide some reference for the follow-up research.

2 Experimental program

2.1 Preparation of the specimens

A total of thirteen square nano-concrete-filled steel tubular columns [13] with end plates [14] were designed to understand the behavior of columns after lateral impact. The columns are composed of nano-concrete, steel tube, and two steel plates. The nano-concrete was filled in the steel tube first. Then wait for the nano-concrete curing to be completed. The steel plate was welded [15] to each end of columns after nano-concrete curing. Side length of all square columns (l) is 150 mm. The side length of end

Figure 1: Strain gauges arrangement.

plates is 20 mm longer than the columns and thickness of end plates is 10 mm [16]. The size of the columns is presented in Figure 1.

The lateral impact loading (h), steel tube thickness (T) [17], and column height (H) [18] are set as the test parameters in the study. The lateral impact loading refers to the loading applied by the hammer falling freely from a certain height to the impact location of columns [19]. Three kinds of impact loading height are set in the test, including 1,000 mm impact loading height, 1,500 mm impact loading height, and 2,000 mm impact loading height. In order to investigate effect of steel tube thickness on columns, the tubular thickness is set including 3, 4, and 5 mm. The column height is set in the test including 500, 600, and 700 mm.

In order to clearly distinguish each column with different test parameters, the unique column label is given to the test columns. The column label consists of the information of lateral impact loading height, steel tube thickness, and column height. Take the label of column of T4-H600-h1500 as an example; T4 indicates that the steel tube thickness is 4 mm, H600 refers that the column height is 600 mm, and h1500 denotes that the lateral impact height is 1,500 mm.

2.2 Test materials

The nano-concrete was prepared according to the mix proportion of nominal concrete whose nominal compressive strength was 30 MPa. Compared with nominal concrete, the biggest difference of Nano-concrete is the addition of Nano SiO₂. The Nano SiO₂ which is used in the test is Evonik A380 with specific surface area of 380 m²·g⁻¹ and particle size of 7 nm. The properties of Nano SiO₂

Table 1: Properties of nano SiO_2

Material	Properties
Specific surface area: $380 \text{ m}^2 \cdot \text{g}^{-1}$
	Mean particle size: 7 nm
	Apparent density: $\approx 30 \text{ wt}\%$
	Bulk density: $\approx 50 \text{ wt}\%$
	SiO_2 content: $>99.8\%$
Nano SiO_2	

are presented in Table 1 [20]. The detail mix proportion of nano-concrete is presented in Table 2. The compressive strength of the nano-concrete is tested with three cubic specimens of $150 \times 150 \times 150 \text{ mm}$ [21]. The test cubic specimen is cured under the same conditions of nano-concrete used. The test results of the cubic specimen are presented in Table 3.

The Standard Q235 steel is used in the test to fabricate the outer steel tube. Nominal yield strength of the steel is 235 MPa. In order to get the actual yield strength (f_y) and tensile strength (f_u) of the steel tube, three tensile coupons were tested according to the Metallic Materials (GB/T 228-2002) [22]. The results are presented in Table 4.

2.3 Lateral impact test

Eleven square nano-concrete-filled steel tubular columns with end plates were tested with the lateral impact [19]. The impact tests were carried out with drop hammer test setup [23]. The hammer which was used weighed 339 kg. The different lateral impact loading was applied by changing the free fall height of hammer. The square column was fixed on the impact platform, designed impact location aligned with hammer head, which was used to make sure that square columns absorbed the impact energy. The impact location was the middle location of the square columns. During the impact test, the impact hammer was

Table 3: Results of nano-concrete cubes tested

Design strength (f_c)	Test cube	Cubic compressive strength (f_{cu} /MPa)	Average value (f_{cu} /MPa)
C30	No. 1	37.5	37.23
	No. 2	35.9	
	No. 3	38.3	

stretched to design height by the winch. And then the hammer free fall down.

2.4 Compression test

Before the compression test, seven square columns were selected to attach the strain gauges [24]. The seven columns are T3-H700-h2000, T4-H700-h2000, T5-H700-h2000, T4-H600-h1000, T4-H600-h1500, T4-H600-h2000, and T4-H500-h2000. For each square column-attached strain gauge [25], the strain development data of four points of the column were collected. For each point, the data of longitudinal strain development and transverse strain development were attached. The strain gauge attached locations of square columns are shown in Figure 1.

After lateral impact test, all thirteen square nano-concrete-filled steel tubular columns with end plates were subjected to the compression test. The electro hydraulic servo universal testing setup with ultimate capacity of 5,000 kN was used [26]. The method of multi-stage load was used to apply the compressive loading for the square columns according to estimated ultimate capacity. Estimated ultimate [27] capacity (N^e) of the square nano-concrete-filled steel tubular column with end plates is calculated as following:

$$N^e = f_y \times A_s + f_{cu} \times A_c \quad (1)$$

where A_s denotes the area of steel and A_c refers to the area of nano-concrete in the cross section of square columns. Before applied loading is not over 60% of estimate ultimate capacity, the applied loading is gradually increased by 1/10 of estimated ultimate capacity at each stage. When applied loading is over 60% of estimate

Table 2: Mixture proportions of nano-concrete

Concrete mixture	Water	Cement	Fine aggregate	Coarse aggregate	Nano SiO_2 (wt%)	Water reducer (wt%)
Nano-concrete	1	0.4	1.65	2.5	1.0	1.0

Table 4: Tested results of steel tube properties

Properties test	Yield strength [f_y] (MPa)	Average yield strength [f_y] (MPa)	Tensile strength [f_u] (MPa)	Average tensile strength [f_u] (MPa)
P1	276	269	348	347
P2	263		351	
P3	268		342

(a)

(b)

Figure 2: Failure of square columns: (a) failure mode of LBM and (b) failure mode of LBE.

ultimate capacity, the applied loading is gradually increased by 1/20 of estimated ultimate capacity at each stage. For each stage of compression test, the latest applied loading is maintained for 2 min. Two criteria are used to judge whether the square column is a failure [27]: (1) When axial displacement reaches to 10% of the length of the specimen, specimen is confirmed to be failed. (2) When applied loading is increased to the max value, then decreasing as the test continued, specimen is confirmed to be failed.

3 Test results

In subsequent sections, the failure mode, ultimate capacity, initial stiffness, and ductility of square nano-concrete-filled steel tubular columns with end plates after lateral impact under axial compression test are discussed. But before that, the secant stiffness method is introduced to define the ductility coefficient (μ) [28] ($\mu = \Delta_u/\Delta_y$) and the initial stiffness (k) [29] ($k = N_{r35\%}/\Delta_{35\%}$). Yield displacement (Δ_y) being eliminated the initial settlement is equal to $\Delta_{80\%}/0.8$; $\Delta_{80\%}$ or $\Delta_{35\%}$ is the axial displacement when the load attains 80 or 35% of the ultimate load in the pre-peak stage. And Δ_u is the ultimate displacement being eliminated the initial settlement when the load attains the ultimate load. The value of $N_{r35\%}$ is equal to 35% of the ultimate load.

3.1 Failure modes

The local buckling [30] development of square nano-concrete-filled steel tubular columns with end plates under axial loading is the main failure mode. The difference of

the failure mode is the development location of local buckling. When the local buckling is developed at the impact location, the failure mode is named LBM which is presented in Figure 2(a). And when the local buckling is developed at the end of the columns, the failure mode is named LBE which can be seen from Figure 2(b). The failure modes of every square columns are presented in Table 5. It can be found that when square columns are subjected to lateral impact loading, local buckling is developed around the impact location. When the square columns are not subjected to the lateral impact loading, local buckling is developed at the end of square columns. The steel tube is weakened at the end of square column due to the welding of the end plate, resulting in that the local buckling was developed at the end of the specimen under axial load. However, when square column is subjected to lateral impact loading, the concrete at impact location is broken and the steel tube had a certain deformation, so the local buckling is developed around the impact location under axial compression test. The further discussion of the effects boundary conditions on the buckling failure can be continued by the method of David [31] in the next investigation.

3.2 Load–displacement curves

The ultimate capacity, initial stiffness, and ductility of square nano-concrete-filled steel tubular columns with end plates after lateral impact can be obtained from the load–displacement curves [32]. Load–displacement curves of square columns with different test parameters are presented in Figure 3. From this figure, when the applied loading is increased to the maximum, bearing

Table 5: Test results of specimens

Specimen	H/l	l/T	Δ_u (mm)	Δ_y (mm)	μ	k (kN·mm ⁻¹)	N_r (kN)	Failure modes
T3-H700-h2000	4.67	50.0	9.24	7.21	1.28	106.89	1240.20	LBM
T4-H500-h1000	3.33	37.5	10.83	9.17	1.18	69.58	1450.80	LBE-LBM
T4-H500-h1500	3.33	37.5	6.40	5.00	1.28	122.12	1396.40	LBM
T4-H500-h2000	3.33	37.5	10.91	7.26	1.50	103.21	1347.40	LBM
T4-H600-h1000	4.00	37.5	7.85	6.11	1.29	106.43	1533.60	LBM
T4-H600-h1500	4.00	37.5	9.49	5.84	1.62	131.72	1430.00	LBE-LBM
T4-H600-h2000	4.00	37.5	8.90	7.26	1.22	115.06	1338.60	LBE-LBM
T4-H700-h0	4.67	37.5	7.95	6.84	1.16	112.84	1697.20	LBE
T4-H700-h2000	4.67	37.5	8.22	5.23	1.57	164.37	1345.20	LBM
T5-H500-h0	3.33	30.0	8.45	6.03	1.40	167.39	1766.60	LBE
T5-H500-h2000	3.33	30.0	4.49	3.30	1.36	246.99	1419.80	LBM
T5-H600-h2000	4.00	30.0	7.32	5.02	1.46	159.17	1588.40	LBM
T5-H700-h2000	4.67	30.0	6.44	4.96	1.30	151.46	1490.80	LBM

Figure 3: Load–displacement curves: (a) T4-h2000, (b) T5-h2000, (c) T4-H500, (d) T4-H600, and (e) H700-h2000.

capacity of square column is not decreased obviously, but the corresponding displacement is continuously increased with the test. This indicates that the ductility of the square columns is well [33]. The ultimate capacity

of the square column is decreased because of lateral impact loading. And ultimate capacity is increased with the increase of steel tube thickness. The initial stiffness has a little increase with the increase of column height.

Figure 4: Load-strain curves (a) T3-H700-h2000, (b) T4-H700-h2000, (c) T5-H700-h2000, (d) T4-H600-h1000, (e) T4-H600-h1500, (f) T4-H600-h2000, (g) T4-H500-h2000.

3.3 Load–strain curves

In order to investigate the strain development [34] of square nano-concrete-filled steel tubular columns with end plates after lateral impact under axial loading, the strain development data of each point are collected. The load–strain curves [35] are presented in Figure 4. In this figure, positive strain value refers to tensile strain and the negative strain value refers to compression strain. From the figure, it could be found that the value of strain at the location of the corner point of the columns is bigger than other two points. Furthermore, the strain value of corner point on the surface which is subjected to the lateral impact loading is bigger than that of the corner point of side surface of impact location. It indicated that the corner location of square columns is easier damaged than that of other locations. And the corner of impact surface of the square columns is easier damaged than

that of other corner locations. It also can be found from this figure that the strain value of the square column is decreased with the increasing steel tubular thickness. The effects of column height on the strain development of square columns are not obvious. As for the effects of lateral impact loading on strain development of square columns, the strain development is more complex with the increasing lateral impact loading.

3.4 Ultimate capacity

The effects of lateral impact loading on ultimate capacity [36] of square nano-concrete-filled steel tubular columns with end plates are discussed in this part. It can be easily concluded from Table 5 and Figure 5(a) that the ultimate capacity of square columns is reduced because of the

Figure 5: Effects of test parameters on ultimate capacity: (a) effect of lateral impact, (b) effect of steel tubular thickness, and (c) effect of column height.

lateral impact loading. When the test parameters of steel tubular thickness and column height are constant, the ultimate capacity is decreased 6.8% of the ultimate capacity of T4-H600-h1000 when the lateral impact height is increased from 1,000 to 1,500 mm, and ultimate capacity is decreased 6.4% of the ultimate capacity of T4-H600-h1500 when the lateral impact height is increased from 1,500 to 2,000 mm. One conclusion should be pointed out that when the column height of square column is changed from 600 to 500 mm and steel tube thickness is constant, the reduction of ultimate capacity is decreased with the increase of lateral impact loading height. The results indicate that the negative effects of lateral impact loading on capacity of square columns can be reduced by appropriately reducing height of square columns.

The effect of steel tubular thickness on ultimate capacity of square nano-concrete-filled steel tubular columns with end plates is obvious. It is presented in Figure 5(b) that the ultimate capacity of square column is greatly

increased with the increase of steel tubular thickness when the column height and lateral impact loading height are constant. For example, when the column height is 700 mm and lateral impact loading height is 2,000 mm, ultimate capacity is increased from 1240.20 to 1345.20 kN with the steel tubular thickness increasing from 3 to 4 mm. The capacity of square columns is increased by 8.5%. When the steel tubular thickness is increased from 4 to 5 mm, the ultimate capacity of square column is increased from 1345.20 to 1490.8 kN. The capacity of square columns is increased by 10.8%.

The conclusion can be found from the Figure 5(c) that the ultimate capacity of square nano-concrete-filled steel tubular columns with end plates has a slight decrease with the increase of column height. When the steel tubular thickness is 5 mm and lateral impact loading height is 2,000 mm, the ultimate capacity is decreased from 1588.40 to 1490.80 kN with the column height increasing from 600 to 700 mm. It could be found that the ultimate

Figure 6: Effects of test parameters on initial stiffness: (a) effect of lateral impact, (b) effect of steel tubular thickness, and (c) effect of column height.

Figure 7: Effects of test parameters on ductility: (a) effect of lateral impact, (b) effect of steel tubular thickness, and (c) effect of column height.

capacity of square column with column height of 600 mm is higher than that of other two kinds of column height when the steel tubular thickness is 5 mm and lateral impact loading height is 2,000 mm. But when the steel tubular thickness is 4 mm and lateral impact loading height is 2,000 mm, the ultimate capacity of square column is not affected by the test parameter of column height. It indicates that the effect of column height of square nano-concrete-filled steel tubular columns with end plates after lateral impact can be reduced by reducing the steel tubular thickness.

3.5 Initial stiffness

The initial stiffness [37] of square nano-concrete-filled steel tubular columns with end plates is affected by the lateral impact loading which is presented in Table 5 and Figure 6(a). It could be concluded that initial stiffness of

square column is increased with the increase of lateral impact loading height when the test parameters of steel tubular thickness and column height are constant. For example, when the steel tubular thickness is 4 mm and column height is 500 mm, the initial stiffness of square column is increased from 69.58 to 122.12 kN·mm⁻¹. When the steel tubular thickness is 4 mm and column height is 600 mm, the initial stiffness of square column is increased from 106.43 to 131.72 kN·mm⁻¹. But, it also can be found that the initial stiffness has a slight decrease when lateral impact loading is increased from 1,500 to 2,000 mm. It indicates that when lateral impact loading height is increased to a certain height, the effect to the initial stiffness of square column is negative. The determination of this key value of lateral impact loading height will be further discussed in the later research.

The initial stiffness of square nano-concrete-filled steel tubular columns with end plates after lateral impact is increased with the increase of steel tubular thickness

which can be easily found from Figure 6(b). For example, when lateral impact loading height is 700 mm and column height is 2,000 mm, the initial stiffness of square column is increased from 106.89 to 164.37 kN·mm⁻¹ with the increase of steel tubular thickness from 3 mm to 4 mm. The initial stiffness of square column is increased 53.8%. But, when the steel tubular thickness is increased from 4 to 5 mm, the change of initial stiffness of square column is not obvious. It indicates that when the steel tubular thickness is increased to a value greater than 4 mm, the effect of steel tubular thickness on the initial stiffness is no longer obvious.

Effect of column height on initial stiffness of square nano-concrete-filled steel tubular columns with end plates after lateral impact is not regular which could be seen from the Figure 6(c). When the steel tubular thickness is 4 mm and lateral impact loading height is 2,000 mm, initial stiffness of square column is increased with the increase of column height. But when the steel tubular thickness is 5 mm and lateral impact loading height was 2,000 mm, initial stiffness of square column is decreased with the increase of column height. The results can meet the conclusion of the effect of steel tubular thickness on initial stiffness of square columns.

3.6 Ductility

The effect of lateral impact loading on ductility [38] of square nano-concrete-filled steel tubular columns with end plates is significant which could be found from

Figure 7(a). The ductility of square column is increased with the increase of lateral impact loading height. It can be seen from Table 5 that the ductility of square column is increased from 1.18 to 1.28 with the increase of lateral impact loading height from 1,000 to 1,500 mm when the steel tubular thickness is 4 mm and column height is 500 mm. And when the steel tubular thickness is 4 mm and column height is 500 mm, the ductility of square column is increased from 1.28 to 1.50 with the increase of lateral impact loading height from 1,500 to 2,000 mm. But, when column height is increased to 600 mm, improvement of ductility of square column has a slight decrease. It indicated that effect of lateral impact loading on the ductility can be reduced by increasing the column height.

From the Figure 7(b), it can be found that when the column height is 700 mm and lateral impact loading height is 2,000 mm, ductility of square column after lateral impact with the steel tubular thickness of 4 mm is better than that of other two kinds of steel tubular thickness. And when the steel tubular thickness is 3 or 5 mm, the ductility of square column is similar. The result indicated that there is a value of steel tubular thickness which is greater than or equal to 4 mm but less than 5 mm. When the steel tubular thickness is under the value, the ductility of the square column is increased with the increase of steel tubular thickness, but when the steel tubular thickness is increased over value, the ductility of the square column is decreased with the increase of steel tubular thickness.

Effect of column height on ductility of square nano-concrete-filled steel tubular columns with end plates after lateral impact is presented in Figure 7(c). Whenever

Table 6: Calculated ultimate capacities of specimens

Specimen	H/l	l/T	N _r (kN)	η	N _{re} (kN)	N _r /N _{re}	Error
T3-H700-h2000	4.67	50.0	1240.20	1.00	1165.79	0.94	-0.06
T4-H500-h1000	3.33	37.5	1450.80	0.50	1436.29	0.99	-0.01
T4-H500-h1500	3.33	37.5	1396.40	0.75	1368.47	0.98	-0.02
T4-H500-h2000	3.33	37.5	1347.40	1.00	1293.50	0.96	-0.04
T4-H600-h1000	4.00	37.5	1533.60	0.50	1441.58	0.94	-0.06
T4-H600-h1500	4.00	37.5	1430.00	0.75	1372.80	0.96	-0.04
T4-H600-h2000	4.00	37.5	1338.60	1.00	1298.44	0.97	-0.03
T4-H700-h0	4.67	37.5	1697.20	—	1584.45	0.93	-0.07
T4-H700-h2000	4.67	37.5	1345.20	1.00	1304.84	0.97	-0.03
T5-H500-h0	3.33	30.0	1766.60	—	1749.60	0.99	-0.01
T5-H500-h2000	3.33	30.0	1419.80	1.00	1434.00	1.01	0.01
T5-H600-h2000	4.00	30.0	1588.40	1.00	1429.56	0.90	-0.10
T5-H700-h2000	4.67	30.0	1490.80	1.00	1431.17	0.96	-0.04
Maximum						1.01	0.01
Minimum						0.90	-0.10
Average value						0.96	-0.04
Variance						0.000739	0.000739

the steel tubular thickness is 4 or 5 mm, the ductility of square column is increased with the increase of column height from 500 to 600 mm when the lateral impact loading height is 2,000 mm. But when column height is increased from 600 to 700 mm, ductility is a little decreased. The result indicates that when column height is increased to over 600 mm, the effects of increasing column height on ductility are negative.

4 Calculate formula

It can be found from the test result and discussion above that the effect of lateral impact loading is obvious on the ultimate capacity. The influence factor of lateral impact loading must be considered in calculating the ultimate capacity. The normal calculation formula [39] of square CFST columns is shown as following:

$$N_0 = A_{sc} \times f_{scy} \quad (2)$$

$$f_{scy} = (1.18 + 0.85\xi) \times f_{cu} \quad (3)$$

$$A_{sc} = A_s + A_c \quad (4)$$

$$\xi = \alpha \times f_y / f_{cu} \quad (5)$$

$$\alpha = A_s / A_c \quad (6)$$

where A_s and A_c are the cross section area [40] of steel and nano-concrete, respectively. The calculated ultimate capacities of specimen without the damage of lateral impact are 1426.11 kN ($T = 3$ mm), 1584.45 kN ($T = 4$ mm, error is 6.6% compared with the test result), and 1749.60 kN ($T = 5$ mm, error is 1.0% compared with the test result). It denotes that the normal calculation formula can be used to calculate the columns without the lateral impact damage.

Based on the normal calculation formula, the ultimate capacity of nano-concrete-filled steel tubular columns with end plates after lateral impact is calculated by introducing the influence coefficient (η) of lateral impact loading. The assumed functional forms of the calculation formula are as follows:

$$N_{rc} = f(\eta) \times N_0 \quad (7)$$

$$f(\eta) = 1 - 0.18 \times \eta \quad (8)$$

$$\eta = h/2,000 \quad (9)$$

The calculated results are shown in Table 6. The calculated results are compared with the test results. The value of N_{rc}/N_r is calculated in the Table 6. The maximum of N_{rc}/N_r is 1.01, the minimum is 0.90, the average value is 0.96, and the variance value [41] is 0.000739. It

illustrates that the calculated result is in good agreement with the test results.

5 Conclusion

The effects of lateral impact loading, steel tubular thickness, and square column height on mechanical behavior of nano-concrete-filled steel tubular columns with end plates are studied in this paper. Failure mode, ultimate capacity, initial stiffness, and ductility of square columns are analyzed. The following conclusions can be obtained from the analysis:

1. Ultimate capacity of nano-concrete-filled steel tubular columns with end plates is greatly decreased because of the lateral impact loading. And ultimate capacity of square column is decreased with the increase of lateral impact loading height. The improvement of ultimate capacity of square column by increasing the steel tubular thickness is obvious.
2. The initial stiffness of nano-concrete-filled steel tubular columns with end plates is increased with the increase of lateral impact loading height. And initial stiffness of square nano-concrete-filled steel tubular columns with end plates is increased with the increase of steel tubular thickness. But effect of column height on initial stiffness of square columns is not regular.
3. The effect of lateral impact loading on ductility of square nano-concrete-filled steel tubular columns with end plates is great. And the ductility of square column is increased with the increase of lateral impact loading height. When the steel tubular thickness is increased under a value, the ductility of the square column is increased with the increase of steel tubular thickness. However, when the steel tubular thickness is increased over value, the ductility of the square column is decreased with the increase of steel tubular thickness. When column height is increased over 600 mm, the effects of increasing column height on ductility are negative.

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