A Comparative Test Study of the Impact Performances of Stainless-Steel Rebar Equal-Strength Replacement Piers

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Abstract

It has been found that there are rebar instability and construction complexity phenomena associated with the replacements of ordinary pier rebars with stainless-steel rebars of equal piece numbers and strength. Therefore, this study explored the issues of the equal-strength replacements of stainless-steel pier rebars with different distributions. The study utilized the most advanced domestic multi-function super-high heavy hammer impact test system available, and conducted a comparative test of the horizontal impact results of two groups of pier models with 1/5 contraction scales. The purpose of the testing was to analyze the impact force, impact displacement, strain time history curve, crack propagation and distribution, ultrasonic damages to the concrete, and so on. The test results showed the following: The original specimen displayed a consistent variation trend with the equal replacement specimen of the stainless-steel rebar of different distributions from the aspects of the maximum impact force, strain of the rebar and concrete, displacement peak, and so on, under the conditions of continuous multiple impacts. The relative variation rate was found to be within the scope of $\pm 10\%$ under equal impact energy. The quantity and distribution of the cracks, as well as the concrete damages, were also found to be approximately consistent under equal impact energy. Therefore, in this study, it was considered to be feasible for the solution of the problems related to rebar corrosion, strength surplus, resource waste, and so on, to replace ordinary pier rebars with stainless-steel rebars with equal-strength and different distributions.

Keywords Reinforced concrete piers · Different distributions · Stainless-steel rebar · Equal-strength replacement · Impact performances

1 Foreword

With the development of China's economy and infrastructure, the construction of bridges across rivers and seas has developed rapidly. Also, the navigation densities of the crossing channels have been increasing daily. At the same time, ships tend to be very large-scale, fast-moving, and professional. The shipping speeds and tonnage have also constantly increased, which has resulted in frequent occurrences of ship-bridge collision accidents (Zhou et al. 2018a, b;

Zhong et al. 2018; Zhang 2007). Since stainless-steel materials have displayed good corrosion resistance performances, they have begun to play important roles in improving the safety and durability of structures (Sarno et al. 2003). Moreover, during the construction of such structures (important bridge structures in particular), stainless-steel rebars have been increasingly utilized instead of ordinary rebars (Wang et al. 2010; Yuan et al. 2011). At the present time, stainless-steel rebars with equal cross-sections are mainly used in projects to replace the ordinary rebars commonly used in bridge pier construction. However, this type of replacement method is characterized by problems related to surplus strength, resource waste, and so on, due to the much higher strength of the stainless-steel rebars compared to ordinary rebars. There has been a rebar instability and construction complexity phenomenon observed when replacing the ordinary rebars of piers with stainless-steel rebars with equal pieces and strength. This study proposed viable solutions to the aforesaid problems by replacing the ordinary rebars with

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stainless-steel rebars of equal strength and different distributions. In other words, the members had the equivalent axial load carrying capacities in the unit areas. However, they had different rebar distributions.

This study's examination of stainless-steel reinforced concrete structures was mainly focused on corrosion resistance and static performances. The results showed that the corrosion resistance of the stainless-steel reinforced concrete was much higher than that of the ordinary reinforced concrete (Gao et al. 2018; Deng et al. 2014; Yang et al. 2013; Garcia-Alonso et al. 2007). Meanwhile, the bond strengths of the stainless-steel reinforced concrete and ordinary reinforced concrete were found to be basically the same (Li et al. 2016; Zhang and Wu 2008). Furthermore, the stainless-steel rebars displayed good ductility and energy dissipation capacities (Mi 2017; Zhang et al. 2011; Zhang and Zhao 2010). It was determined that the good ductility of the stainless-steel rebars allowed the stainless-steel reinforced concrete structures to absorb large amounts of energy without undergoing damages under impact. In some of the previous research studies regarding the impact mechanical properties of ordinary reinforced concrete structures, the following achievements have been made: The dynamic responses and failure modes of structures were determined, such as the time histories of the impact forces, acceleration time histories, strain time histories, displacement time histories, and so on (Zineddin and Krauthammer 2007; Ohnuma et al. 1985). The impact load durations and peak values were determined to be the important factors in determining the failure modes of the structural members (Liu et al. 2010). The effects of the influence mechanisms of the impact velocities, reinforcement ratio of rebars, concrete strength, constraint conditions, hammer rigidity, and so on, on the dynamic performances of the structures were evaluated (Louw 1992; Kishia et al. 2002; Sukontasukkul and Mindess 2003). The increases in the reinforcement ratios of the longitudinal bars and stirrup have been found to effectively improve the impact resistance of reinforced concrete columns (Tian et al. 2013). Changes in the reinforcement ratios also were determined to influence the failure modes of structures under the lateral impact conditions (Qian 2015). The increases in the reinforcement ratios and the sectional dimensions of the longitudinal bars can significantly reduce node displacements in columns; however, such effects were not obvious for the stirrup (Zhang et al. 2009). The dynamic performances of the failures under one-time and cumulative impacts were examined (Rajagopalan et al. 1995; Wang et al. 1996). It should be noted that the individual research studies regarding the impact mechanical performances of stainless-steel reinforced concrete structures have presented results which have indicated that the variation trends of the impact forces, displacement peaks, and impact energy were consistent with the secondary function curves (Chen 2015). Stainless-steel

reinforced concrete structures have displayed better impact resistance performances than ordinary reinforced concrete structures (Zhang et al. 2017). Current research shows that stainless steel bars with equal strength (with the same number of longitudinal bars) can be used to replace ordinary bars in piers (Zhou et al. 2018a, b), but this method has some problems, such as instability of steel bars and complex construction. Therefore, this paper intends to use different distributions of stainless steel bars to replace ordinary steel bars in piers.

This research study used the most advanced domestic multi-function super-high heavy hammer impact test system to conduct a comparative experimental study on the impact performances of stainless-steel rebars with the equal strength (load-bearing capacity of the rebars in the unit area of the cross-section) and different distributions, and those of ordinary pier rebars.

2 Impact Test

2.1 Test Device

In this study, impact testing was conducted using the most advanced domestic multi-function super-high heavy hammer test machine system. The test machine system consisted of a vertical hammer driving system and a horizontal impact system, as shown in Fig. 1a. The kinetic energy of the horizontal collision test car (as shown in Fig. 1b) was provided by the vertical hammer driving system (Fig. 1c). The test car was equipped with a rigid impact hammer in the front. There were four specially designed steel round cylinder installation pressure sensors located between the hammer and the car, as shown in Fig. 1d. The track was equipped with a laser speed measurement system at the end in order to measure the transient speed when the collisions occurred.

The impact speed (kinetic energy) of the car was related to the lifting height and mass of the drop hammer, as well as the mass of the car. In this experiment, the maximum lifting height of the drop hammer was 18 m, the mass of the drop hammer was 166 kg and the mass of the test car was 1200 kg.

2.2 Test Specimen

A comparative experimental study method was used to examine the impact performances of stainless-steel rebars with equal strength and different distributions, and those of ordinary rebars. The test designed two groups of comparative specimens of stainless-steel reinforced concrete, and ordinary steel reinforced concrete round piers. These two groups of specimens had column sectional radii of 170 mm, and heights of 2200 mm. The stirrup was a I grade ordinary

Fig. 1 **a** Multi-function super-high heavy hammer test machine system; **b** horizontal collision test car; **c** vertical hammer drop; **d** device pressure sensor

Fig. 2 Reinforcement diagram of the specimens (mm)

rebar HPB300 with a diameter of 8 mm, and it adopted a welding construction method (details shown in Fig. 2). Each group of specimens had different types, pieces, and diameters of longitudinal rebars. In other words, these two groups

Table 1 Numbering and design parameters of the test specimens

Specimen no	Longitudinal reinforcement (mm)	Stirrup (mm)	Concrete strength grade
Z1-20	8S20	Φ8@50	C40
Z2-22	10Φ22	Φ8@50	C40
Z3-20	6S20	Φ8@50	C40
Z4-22	8Φ22	Φ8@50	C40

Note: S represents the stainless-steel rebar (S2304)

of longitudinal rebars had different distributions. Among the specimens, the longitudinal rebars used for the stainless-steel rebar concrete columns were S2304 two-phase stainless-steel rebars (UGIGRIP1.4362) produced by UGITECH Co. (France). Meanwhile, the longitudinal rebars used for the ordinary reinforced concrete columns were HRB335 rebars. The numbering and design parameters of the pier model are shown in Table 1. The longitudinal rebars used for the specimens, as well as their distributions, are shown in Fig. 3.

During the experimental testing process, sampling performed for the rebars in the specimens, and a loading tension

Fig. 3 Longitudinal reinforcements and distributions of the specimens (mm)

test was performed using electro-hydraulic servo universal testing machines. The yield strengths and ultimate strengths of the stainless-steel and ordinary rebars were thereby obtained. The stresses of the stainless-steel rebars with 0.2% residual strain as the yield strength was determined, and the details are shown in Table 2. Meanwhile, 12 cubic specimens (150 mm × 150 mm × 150 mm) were made as per the requirements, and compression tests were then completed on the specimens.

There is a formula for the vertical bearing capacity of the component:

$$N = 0.9\varphi(N_C + N_S) \quad (1)$$

N —Standard value of axial bearing capacity; φ —The stability coefficient of the axial compression member,

N_C —Concrete bearing capacity, N_S —Bearing capacity of steel bar.

For reinforced concrete members, the section area of the reinforced bar is usually converted into an imaginary area of the tensile concrete section, so that the material mechanics formula can be used to calculate the cross-section. The flexural stiffness of each component section can be obtained by the following calculation:

$$EI = E_C \times I_0 = E_C \times \frac{\pi d_0^4}{64} \quad (2)$$

E_C —Elastic modulus of concrete; I_0 —Moment of inertia of cross-section; d_0 —Equivalent section diameter of reinforced concrete;

According to formulas (1) and (2), the comparison of the equal-strength replacements of the pier specimens is shown in Table 3.

As can be seen in Table 3, the axial load-bearing capacities of the pier specimens changed following the equal-strength replacements of the two groups of stainless-steel rebars. However, their relative ratios were within $\pm 1.5\%$. Also, it was determined that the stainless-steel rebars of equal strength and different distributions could be effectively used to replace the ordinary rebars used in the pier. The flexural rigidity of the cross-sections was observed to be reduced after the equal-strength replacements. However, the relative ratio was determined to be smaller than 3%, and the changes in the flexural rigidity of the members was extremely small before and after the equal-strength replacements. Therefore, according to this study's analysis results, from the perspective of the axial load-bearing capacities of the members, and the flexural rigidity of the cross-sections, it was deemed feasible to replace ordinary rebars used in

Table 2 Basic parameters of the rebars

Reinforcement type	Steel diameter	Elastic modulus (N/mm ²)	Yield strength (N/mm ²)	Ultimate strength (N/mm ²)	Ratio ultimate-to-yield strength
Stainless-steel reinforcement	S20	1.93×10^5	729	858	1.18
Ordinary reinforcement	Φ22	2.0×10^5	368	552	1.5

Table 3 Comparison of the equal-strength replacements of the pier specimens

Group	Specimen number	Individual bar bearing capacity (N)	Reinforcement number	Concrete strength (N/mm ²)	Vertical bearing capacity (N)	Vertical bearing capacity relative ratio (%)	Bending stiffness of section ($\times 10^{12}$ N/mm ²)	Relative ratio (%)
—	Z1-20	221,340	8	41.69	5,555,840	0.68	27.55	−2.58
	Z2-22	173,300	10		5,518,120		28.28	
二	Z3-20	221,340	6		51,129,120	−1.13	28.63	−2.35
	Z4-22	173,300	8		51,715,120		29.32	

piers with stainless-steel rebars of equal strength. The main difference was that the differences in the number of longitudinal rebars in a pier before and after the replacements will lead to different distributions of the longitudinal rebars. Therefore, it was important to examine the influences of the rebar distributions on the impact performances of the equal-strength rebar replacement piers.

2.3 Test Design

A horizontal impact test was conducted on the four specimens of reinforced concrete columns. It was found that the designed impact frequency was four times per column.

The pier specimen was fixed on a rigid base with four prestressed bolts prior to the test, which was approximately equivalent to the constraint of the fixed end. Then, 250 kN of axial pressure was imposed on the upper end of the column using an oil jack which was installed on the beam of the reaction frame, as shown in Fig. 4. After installing the reinforced concrete specimen, an impact test was performed by lifting the drop hammer to the heights of 2, 4, 6, and 8 m, respectively. For all of the test items, the distance from the impact points to the column bottoms was 1100 mm (for example, the center of the specimen). The equivalent design of the heights and locations of impact points was made in accordance with the location and distribution of the impact force which had resulted from ship-bridge collisions.

A NI data collection system (USA) was used in the test in order to acquire the impact force, rebar and concrete strain, and specimen displacement of the two groups of specimens under the effect of horizontal impact loads. A ZBL-U520 non-metal ultrasonic detector was used to detect the concrete damages in the main failure areas of the specimens, and to record the derivation and development status of the

cracks. Also, high-speed photography produced by the AOS Co was used during the entire test to record the collision processes. Among these, the impact force was measured using a pressure sensor mounted at the head position of the impact car. For the specimens of which the lower end was fixed, the upper part was subjected to axial pressure (reverse friction force), the maximum stress and strain occurs on the back side of the impact point and the impact direction of the clamped end. According to the bending moment distribution, 6 steel strain measurement points and 4 concrete strain measurement points were arranged, which were mainly distributed on the back side of the impact point and the two sides of the clamped end; their distributions are shown in Figs. 5 and 6. The lateral displacement was measured using pull lever type resistance displacement meters, which were arranged at 100, 800, 1500, and 2100 mm locations, respectively, from the top to the bottom of the back of the specimen, as shown in Fig. 7.

3 Impact Effects and Dynamic Response Analysis

In this study, using a horizontal impact test, the data regarding the impact effects and dynamic responses of the ordinary reinforced concrete pier, and the stainless-steel reinforced concrete column after equal-strength replacement, and under different impact energies, could be obtained. These mainly included the time history curves of the impact force, and the time history curves of the displacements, as well as the time history curves of the strain of the rebars and concrete.

Fig. 4 Axial pressure device

Fig. 5 Rebar strain measurement points (mm)

Fig. 6 Concrete strain measurement points (mm)

Fig. 7 Displacement measurement points (mm)

3.1 Time History Curve of the Impact Force

Figure 8 shows the time history curves of the impact forces when the drop hammer was lifted to the heights of 4, 6, and 8 m, respectively. In order to describe the dynamic response of two groups of specimens more clearly, appropriate transverse coordinates (impact time) are selected to show the time history curves under different working conditions. It can be seen in the figure that the original and equal-strength replacement specimens displayed consistent time history curves of the impact forces, along with consistent variation trends of the peak values of the impact forces. It was observed that, under the same impact energy, the two groups

of comparative specimens had similar occurrence times of peaks and peak durations. For example, the peak occurrence times were 1.02, 0.9, and 0.78 s, respectively, when the drop hammer heights were 4, 6, and 8 m.

In accordance with the results displayed in Table 4, the relative ratios of the impact force peaks of the stainless-steel equal-strength replacement concrete piers were within the scope of $\pm 10\%$ under the same impact energy. Furthermore, the impact force peaks of the majority of the stainless-steel reinforced concrete specimens were found to be smaller than those of the ordinary reinforced concrete specimens. For example, when the drop hammer height was 4 m, the impact force peak of Z1-20 was 162,811.627 N, while that of Z2-22 was 180,713.126 N. According to the impulse theorem, the impact force of the Z1-20 specimen was longer. These results were determined to have possibly been due to the good ductility and energy dissipation capacity of the stainless-steel rebars (Zhang et al. 2011).

3.2 Time History Curves of the Train

In order to study the dynamic responses of the rebars used in the specimens for the stainless-steel replacement piers of the equal strength and different distributions, six rebar strain measurement points were arranged at the typical stress locations of the longitudinal rebars of the pier in this study's test. As the stress and strain value at the bottom of the impact surface was larger, we planned to take the No. 2 measurement point to analyze it. However, because of the crash of the strain gauge 2 at the measuring point, the 2 point data were missing. Measurement point No. 3 was herein taken as an example, for the purpose of conducting a comparative analysis of the time history of the rebar impact strain of the two groups of specimens.

Similarly, in order to examine the dynamic responses of the concrete used in the specimens for the stainless-steel replacement piers of equal strength and different distributions, four concrete strain measurement points were designed in this study's test. Due to the fact that the concrete damage to the lower part of the back was larger, measurement point No. 4 was herein taken as an example, in order to conduct a comparative analysis of the time history of the concrete strain of the two groups of specimens.

Figures 9 and 10 show the time history of the rebar and concrete strains during the horizontal impact tests, respectively. As can be seen in the figure, the rebars and concrete used in the equal-strength replacement specimens displayed basically consistent time histories of strain and variation trends of peak values. Also, as detailed in Tables 5 and 6, the relative variations of the rebar and concrete strains in the original and stainless-steel rebar equal-replacement specimens were within ± 0.0001 under the same impact energy. Therefore, from the perspective of the rebar and concrete

Fig. 8 **a** Time history of the impact force of the Z1 and Z2 group specimen at the height of 4 m; **b** Time history of the impact force of the Z1 and Z2 group specimen at the height of 6 m; **c** Time history

of the impact force of the Z3 and Z4 group specimen at the height of 6 m; **d** Time history of the impact force of the Z3 and Z4 group specimen at the height of 8 m

Table 4 Quantitative comparison of the impact forces

Drop hammer height (m)	Group	Number	Impact peak (N)	Relative ratio (%)
4	—	Z1-20	162,811.627	−9.91
		Z2-22	180,713.126	
6	—	Z1-20	213,492.211	−8.24
		Z2-22	232,662.181	
	=	Z3-20	217,294.184	−1.92
		Z4-22	221,556.148	
8	=	Z3-20	278,645.687	9.54
		Z4-22	254,369.205	

strains, the stainless-steel rebar of equal strength and different distributions could be used to replace ordinary rebars in piers.

3.3 Time History Curves of the Displacements

Figure 11 shows the time history of the displacements when the drop hammer heights were 4, 6, and 8 m, respectively. It was observed that, under the same impact speed, the equal-strength replacement specimen had basically the same time history of displacement, and variation trend of the displacement peak value. As detailed in Table 7, under the same impact energy, the relative ratio of the displacement peak of the stainless-steel rebar equal-strength replacement concrete pier was within $\pm 10\%$. From the perspective of the displacement, it was concluded in this study that it was feasible to

Fig. 9 **a** Time history curve of the rebar strain at measurement point No. 3 of the specimen Z1 and Z2 at a height of 4 m; **b** Time history curve of the rebar strain at measurement point No. 3 of the specimen Z1 and Z2 at a height of 6 m; **c** Time history curve of the rebar strain

at measurement point No. 3 of the specimen Z3 and Z4 at a height of 6 m; **d** Time history curve of the rebar strain at measurement point No. 3 of the specimen Z3 and Z4 at a height of 8 m

replace the ordinary rebars used in piers with stainless-steel rebars of equal strength and different distributions.

4 Crack Analysis

In accordance with the comparison of this study's test results of the stainless-steel reinforced concrete and ordinary reinforced concrete specimens, it was determined that their crack development was similar (Vandenberg and Liang 2000). The cracks of the two groups of specimens started from the bottom area of the impact surfaces, and continued to derive and develop with the increases in the impact energy. At the same time, the middle areas of the impacted specimens, and the back areas of the impacted specimens, corresponded to the point where the cracks began to occur. Also, the cracks developed under a certain impact energy. Large cracks

occurred at the bottoms of the impacted surfaces when the impact energy reached a certain value. Furthermore, parts of the concrete at the bottoms of the impacted surfaces' backs were crushed. The development characteristics of the cracks were observed to be very consistent with the main stressing characteristics of the specimens. Figure 12 Post-impact damage of the front and back bottom of the specimen. Table 9 shows the numbers, lengths, and maximum widths of the cracks under the different energies within the areas directly below the specimens.

From Fig. 12, we can see that horizontal bending cracks occur at the bottom of each member's impact surface. These cracks are similar to typical bending cracks in nature, thus the failure mode of members is bending failure. The concrete in the back compression zone is partially crushed and the main tendons are flexed. According to the strain value of the steel bar of Table 5 in the height of 6 m and 8 m and

Fig. 10 **a** Time history curve of the concrete strain at measurement point No. 3 of the specimens Z1 and Z2 at a height of 4 m; **b** Time history curve of the concrete strain at measurement point No. 3 of the specimens Z1 and Z2 at a height of 6 m; **c** Time history curve of the

concrete strain at measurement point No. 3 of the specimens Z3 and Z4 at a height of 6 m; **d** Time history curve of the concrete strain at measurement point No. 3 of the specimens Z3 and Z4 at a height of 8 m

Table 5 Quantitative comparison of the rebar strain

Drop hammer height (m)	Group	Number	No.3 strain peak	Relative variation
4	—	Z1-20	−0.00028	−0.00002
		Z2-22	−0.00026	
6	—	Z1-20	−0.00045	−0.00003
		Z2-22	−0.00042	
	=	Z3-20	−0.00075	−0.00003
		Z4-22	−0.00072	
8	=	Z3-20	−0.00083	0.00007
		Z4-22	−0.00090	

Table 6 Quantitative comparison of the concrete strain

Drop hammer height (m)	Group	Number	No.4 strain peak	Relative variation
4	—	Z1-20	0.000521	0.000043
		Z2-22	0.000478	
6	—	Z1-20	0.000603	0.000053
		Z2-22	0.000550	
	=	Z3-20	0.000727	−0.000004
		Z4-22	0.000731	
8	=	Z3-20	0.000942	−0.000054
		Z4-22	0.000996

Fig. 11 **a** Time history curve of the displacement of the specimens Z1 and Z2 at a height of 4 m; **b** Time history curve of the displacement of the specimens Z1 and Z2 at a height of 6 m; **c** Time history

curve of the displacement of the specimens Z3 and Z4 at a height of 6 m; **d** Time history curve of displacement of the specimens Z3 and Z4 at a height of 8 m

the formula ($\delta = \varepsilon \times E$), the stress values of the reinforced bar can be obtained: $\delta_{1-20} = 86.85 \text{ N/mm}^2$, $\delta_{2-22} = 84 \text{ N/}$

mm^2 , $\delta_{3-20} = 160.2 \text{ N/mm}^2$, $\delta_{4-22} = 180$. Compared with the yield strength of stainless steel bars and ordinary bars in Table 2, the tensile steel of all the specimens failed to yield.

As illustrated in Table 8, the stainless-steel reinforced concrete specimens began to experience cracks when the drop hammer height was 2 m, and then developed stability under the gradual cumulative impacts. The ordinary reinforced concrete specimens displayed no cracking when the drop hammer height was 2 m and 4 m, and then cracking suddenly occurred when the drop hammer height was 6 m. This was possibly due to the higher fragility of the ordinary reinforced concrete specimens. Overall, although the stainless-steel reinforced concrete specimens had earlier occurrence times and large crack widths, the crack lengths were found to be smaller compared with the ordinary reinforced concrete specimens. Therefore, in accordance with

Table 7 Quantitative comparison of the top displacements

Drop hammer height (m)	Group	Number	Displacement peak	Relative ratio (%)
4	—	Z1-20	17.238	9.32
		Z2-22	15.769	
6	—	Z1-20	20.040	6.49
		Z2-22	18.818	
	二	Z3-20	22.073	1.77
		Z4-22	21.690	
8	二	Z3-20	23.677	−6.91
		Z4-22	25.434	

Fig. 12 Post-impact damage of the front and back bottom of the specimen **Table 8** Comparison of the numbers, lengths, and maximum widths of the cracks under the different energies within the areas directly below the specimens

Drop hammer Height (m)	First group						Second group					
	Crack quantity		Length of main fracture (mm)		Width of main fracture (mm)		Crack quantity		Length of main fracture (mm)		Width of main fracture (mm)	
	Z1	Z2	Z1	Z2	Z1	Z2	Z3	Z4	Z3	Z4	Z3	Z4
2	2	0	223.9	0	0.03	0	3	0	378.8	0	0.10	0
4	2	0	275.5	0	0.05	0	4	0	413.3	0	0.14	0
6	2	2	334.3	533.8	0.07	0.03	4	3	499.4	535.6	0.21	0.08
8	2	3	408.6	548.2	0.09	0.04	5	5	534.7	562.3	0.29	0.14

this study's analysis of the specimens at the heights of 6 and 8 m, it was believed that the two groups of specimens had consistent derivation and development tendencies for cracks before and after the equal-strength replacements with the stainless-steel rebars of different distributions.

5 Detection of the Concrete Damages

The ultrasonic detections of impact damages have a high sensitivity (Tian et al. 2014), and the concrete damage judgments are mainly made using a criteria of sound velocity, main frequency, wave amplitude, and so on, which are based on the changes in the ultrasonic wave velocity (CECS 21–2000). The following table shows the acoustic parameter values of the concrete damages in the areas approaching the bottoms of the two groups of specimens, before and after the equal-strength replacements of the stainless-steel rebars.

As can be seen in Table 9, after several impacts of the same energy, the average change rates of the sound velocity

of Z1-12 and Z2-18 in the 1st group were -3.67% and -2.27% , respectively. Meanwhile, the average change rates of the sound velocity of Z3-16 and Z4-20 were -2.84% and -2.78% , respectively. Therefore, it was deemed that the change rates of the sound velocity of the concrete pier were similar before and after the equal-strength replacements of the stainless-steel rebars of different distributions.

6 Conclusions

This study performed an impact comparison test on two groups of equal-strength specimens for stainless-steel rebars of different distributions, and analyzed the dynamic responses of the specimens under the effects of horizontal impacts. These responses included the impact effects, strain, time history curve of the displacement, cracks, concrete damages, and so on. The main conclusions which were reached in this study were as follows:

Table 9 Changes in the acoustic parameters following the concrete damages

Specimen	Drop hammer height (m)	Average acoustic velocity (km/s)		Change rate
		Before impact	After impact	
Z1-20	2	4.176	4.172	−0.0010
	4	4.172	4.138	−0.0081
	6	4.138	4.047	−0.0220
	8	4.047	4.044	−0.0007
Z2-22	2	4.156	4.107	−0.0118
	4	4.107	4.065	−0.0102
	6	4.065	4.036	−0.0071
	8	4.036	4.008	−0.0069
Z3-20	2	4.276	4.273	−0.0007
	4	4.273	4.243	−0.0007
	6	4.243	4.201	−0.0099
	8	4.201	4.173	−0.0067
Z4-22	2	4.256	4.252	−0.0009
	4	4.252	4.246	−0.0014
	6	4.246	4.194	−0.0122
	8	4.194	4.136	−0.0138

- (1) For the equal-strength replacements of the stainless-steel rebars of different distributions, it was deemed that the equal-strength replacements of the stainless-steel rebars of different distributions had no influence on the flexural rigidity of the members. This was due to the fact that the relative ratio of the flexural rigidity was smaller than 0.0002%.
- (2) It was determined that the two groups of specimens displayed consistent variation tendencies of impact force, rebar and concrete strain, displacement time history curve, and peak values before and after the equal-strength replacements of the stainless-steel rebars of different distributions. Under the same impact energy, the relative ratio of the peak values of the impact force and the displacement of the stainless-steel equal-replacement concrete pier was found to be within $\pm 10\%$. Also, the relative variations of the peak values of the rebar and concrete strain were within ± 0.0001 . Therefore, it was concluded in this study that the two groups of specimens had approximately consistent impact effects and dynamic responses before and after the equal-strength replacements of the stainless-steel rebars of different distributions.
- (3) Under the impact of the same energy, the derivation and propagation of the impact cracks of the stainless steel reinforced concrete piers were the same. If the average change rate of sound velocity of concrete was less than -4% , it can be considered that the damage of piers was nearly the same after the ordinary steel pier specimens were replaced by stainless steel pier specimens with different distribution and equal strength.
- (4) In this study, based on the above-mentioned conclusions, it was believed that it was feasible to replace ordinary rebars in piers with stainless-steel rebars of equal strength and different distributions.

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