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SEAM STRENGTH OF CORRUGATED PLATE WITH HIGH STRENGTH STEEL

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Abstract

In an effort to increase the values of bolted seam strength, the normally used steel plates are replaced with high strength steel for the corrugated steel plate of 150 by 50mm and 381 by 140mm corrugation. The comprehensive bolted seam tests were conducted to investigate the effect of high strength plate on the bolted seam behaviors. The tests showed that the high strength plate caused the bolt shearing failure at the relatively thick plates in which the increase of seam strength was limited, contrary to the normally used plates. Thus, the normally used bolt was also replaced with a high strength bolt which led to bolt bearing failure and increase in seam strength at these plates. In result, the design values of seam strength can be increased about 20% by the use of high strength plate and the adoptation of high strength bolt at the relatively thick plates.

Key words: Seam Strength, Corrugated Steel Plate, High Strength Steel

1. INTRODUCTION

The longitudinal bolted seams of corrugated steel plate structure have to transmit the axial force from one plate to another, which requires its compressive strength exceeding the transmitting axial force. In many cases, the structural design of corrugated steel plate structures is governed by this requirement because the bolted seam can be one of the weak points in this structure. Design specifications provide the specific values of seam strength which were determined on an experimental basis. These values depend on a nominal plate thickness and bolt arrangement for the current corrugated steel plate.

In an effort to increase the values of seam strength, the effect of high-strength steel on the seam strength has been studied from a series of compressive test on bolted seam for the given bolt arrangements of 150 by 50mm and 381 by 140mm corrugation. The focus is made on the change in the compressive behaviors of bolted seam and the increase in the values of seam strength when the normally used steel plates are replaced with the highe strength steel plates in the same condition. Prior to testing, the values of seam strength were calculated simply by comparison of bolt bearing and bolt shearing strength. The validity of this calculation method is also discussed based on the comparison with test results.

2. CALCULATION OF SEAM STRENGTH

2.1 Material Properties

The structural steel plates currently used for corrugated steel plates in Korea are SS400 for 150 by 50mm corrugation and SS490 for 381 by 140mm corrugation. These are replaced with the high strength steel plates which are SS490 for 150 by 50mm corrugation and SS540 for 381 by 140mm corrugation. The mechanical properties of these steel plates are shown in Table 1.

Table 1. Mechanical properties of structural steel plates

Corrugation (mm)	Spec.	f_y (MPa)	f_u (MPa)	Elongation (%)	Use
150 by 50	SS400	> 245	> 400	> 21	Currently used plate
	SS490	> 285	> 490	> 19	High strength plate
381 by 140	SS490	> 285	> 490	> 19	Currently used plate
	SS540	> 400	> 540	> 16	High strength plate

1) f_y = yield strength of steel plate
2) f_u = tensile strength of steel plate

2.2 Simple Calculation Method of Seam Strength

Japanese Geotechnical Society(1997) suggested the simple calculation method of seam strength by comparison of bolt bearing strength(P_b) and bolt shearing strength(P_s), whichever is less, as follows.

$$S_S = lesser\ of\ P_b\ and\ P_s \tag{2.1}$$

where, S_S = seam strength of bolted seam, kN/m

$P_b = n\,d\,t\,f_b$ = bolt bearing strength, kN/m

$P_s = \dfrac{n\pi d^2}{4}\tau$ = bolt shearing strength, kN/m

n = number of bolts at the bolted seam

d = diameter of bolt, mm

t = thickness of steel plate, mm

f_b = ultimate bearing stress of bolt, MPa (Table 2)

τ = ultimate shear stress of bolt, MPa (Table 3)

The ultimate bearing stresses of steel plates are given in Table 2 based on Japanese Road Bridge Specification(JRA, 2002) and the ultimate shear stress of bolt can be given as 0.577 times of tensile strength of bolt according to Japanese Geotechnical Society(1997). A high-tension bolt of F8.8T(tensile strength=931 MPa, manufacturer suggested value) with a diameter of 20mm is normally used in the current corrugated steel plates. The mechnical properties of high-tension bolts are shown in Table 3.

Table 2. Ultimate bearing stress of structural steel plates(JRA, 2002)

Spec	SS400	SS490	SS540
f_b (MPa)	1,200	1,400	1,560

Table 3. Mechanical properties of high-tension bolts

Class	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)
F8T	> 600	800 ~ 1,000	16
F10T	> 900	1,000 ~ 1,200	14
F13T	> 1,170	1,300 ~ 1,500	12

2.3 Calculation of Seam Strength

The values of seam strength calculated from equation (2.1) are compared with those of design strength for 150 by 50mm(2 bolts per corrugation) and 381 by 140mm corrugation(6 bolts per corrugation), as shown in Table 4 and Table 5.

For 150 by 50mm corrugation, the values of bolt bearing strength for SS400 plate are less than that of bolt shearing at all the plates of nominal thickness. So, the seam strength is determined by bolt bearing strength and no bolt shearing is expected to be occurred for the SS400 plates. This tendency agrees with the design seam strength specified in ASTM(2003)[1]. On the whole, the

[1] ASTM A796/A796M, Standard Practice for Structural Design of Corrugated Steel Pipe, Pipe-Arches, and Arches for Storm and Sanitary Sewers and Other Buried Applications.

values of calculated seam strength seems to be reasonable providing an overestimation of design strength about 5~20%. For the SS490 plate, on the other hand, the values of bolt bearing strength increase about 17% by replacing SS400 with SS490. So, it become greater than that of bolt shearing at the 7.0mm thick plate on which the seam strength is limited by bolt shearing strength without fully utilizing the increased strength of steel plate.

For 381 by 140mm corrugation, the values of bolt bearing strength for SS490 plate are greater than that of bolt shearing at the 6.23mm and 7.01mm thick plate, which gives no further increase in seam strength over 5.45mm thick plates. This tendency agrees with the design strength of ASTM(2003) which shows the constant strength at the 6.23mm and 7.01mm plate. The same tendency is expected for SS540 plate, although the values of bolt bearing strength increase about 11% by replacing SS490 with SS540.

Table 4. Calculated seam strength for 150 by 50mm corrugation (kN/m)

Nominal thickness (mm)	SS400			SS490		
	Calculated strength		Design strength (ASTM)	Calculated strength		Design strength
	Bolt bearing	Bolt shearing		Bolt beaing	Bolt sheaing	
3.2	1,004	2,248[2)]	778	1,171	2,248	Not specified
4.0	1,254		1,061	1,463		
4.5	1,411		1,239	1,646		
5.3	1,656		1,522	1,939		
6.0	1,882		1,770	2,195		
7.0	2,195		2,124	2,561		

1) 2 bolts per corrugation : n = 2 bolts / 0.15m = 13.3 bolts/m

2) M20, F8.8T bolt is used

Table 5. Calculated seam strength for 381 by 140mm corrugation (kN/m)

Nominal thickness (mm)	SS490			SS540		
	Calculated strength		Design strength (ASTM)	Calculated strength		Design strength
	Bolt bearing	Bolt shearing		Bolt beaing	Bolt sheaing	
3.42	1,482	2,655	884	1,646	2,655	Not specified
4.18	1,811		1,226	2,013		
5.45	2,361		1,797	2,624		
6.23	2,699		2,101	3,000		
7.01	3,037		2,101	3,375		

1) 6 bolts per corrugation : n = 6 bolts / 0.38m = 15.8 bolts/m

2) M20, F8.8T bolt is used

3. BOLTED SEAM TEST FOR 150 BY 50mm CORRUGATION

3.1 Material Properties

Table 6 shows the yield and tensile strength of SS400 and S490 plate before corrugation. The data for SS400 plate are from the test report of RIST(1999) and the data for SS490 plate result from the coupon tests. This data shows that the yield strength and tensile strength of SS490 are about 39% and 19% greater than those of SS400, respectively.

Table 6. Coupon test data for 150 by 50mm corrugation plates

	SS400[1)]		SS490	
	f_y (MPa)	f_u (MPa)	f_y (MPa)	f_u (MPa)
Test Results	303 ~ 326	431 ~ 476	405 ~ 468	512 ~ 566
Mechanical Requirements	> 245	> 400	> 285	> 490

1) Test data reported in RIST(1999)

3.2 Test Program

For SS400 plate, the compressive tests on bolted seam had been conducted with a F8.8T bolt of 20mm diameter using 3,000 kN capacity UTM. The results of these tests reported in RIST(1999) are refered in this study. Basically, the same tests were conducted for SS490 plate with the same test setup shown in Fig 1. The test specimen has a length of 440~500mm and a width of 450mm and the number of bolts per corrugation is two. A F8.8T bolt of 20mm diameter was used in the first series of test. The additional tests were conducted with a F12.9T bolt(tensile strength = 1,290MPa) of the same diameter in the case where the bolt shearing failure was occurred in the first series of test.

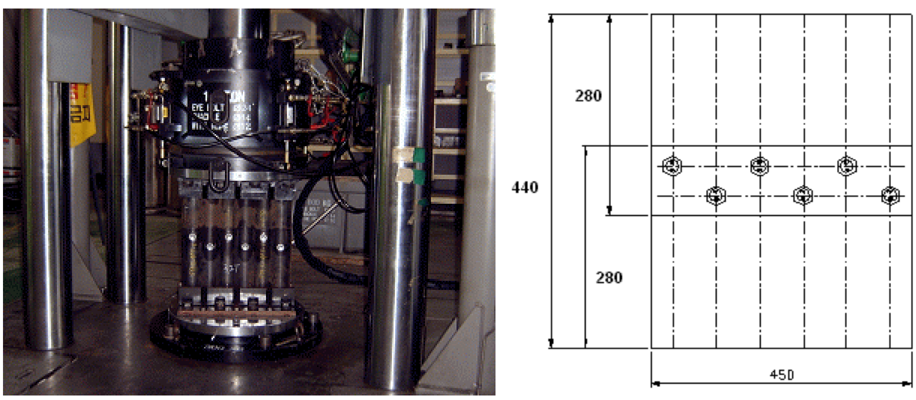


Fig 1. Test setup and specimen for 150 by 50mm corrugation

3.3 Test Results with a F8.8T Bolt

The test results for SS400 plate are summarized in Table 7 and compared with the calculation results from equation (2.1). The values of test strength increased in proportion to specimen thickness as the bolt bearing failure was observed at all the specimens. Compared with these test results, the calculation gives a reasonable estimation in that the diffences in two values of strength are less than 15% and the bolt bearing failure is predicted all the plates.

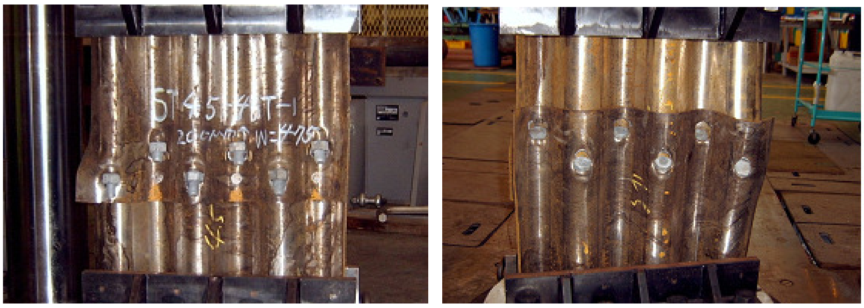
Table 7. Test and calculation results with a F8.8T bolt for SS400 plate

Nominal thickness (mm)	Test Result[1)]		Calculation Result	
	Ultimate Strength (kN/m)	Failure mode	Seam Strength (kN/m)	Failure mode
3.2	925	Bolt Bearing	1,004	Bolt Bearing
4.0	1,140		1,254	
4.5	1,507		1,411	
5.3	1,919		1,656	
6.0	2,006		1,882	
7.0	2,582		2,195	

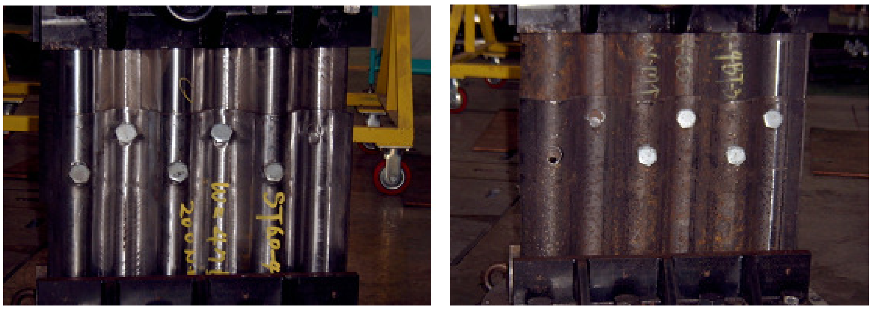
1) Test data reported in RIST(1999)

However, for SS490 plate, the failure mode varied with the specimen thickness, as shown in Fig 2, as the values of strength increased about 20% from those of SS400. Bolt bearing was dominant at the plate less than 5. 3mm thick. The thickness of 6.0 mm seemed critical because bolt shearing together with bolt bearing was observed at two of three specimens and only a bolt bearing was observed at the other one. Finally, the typical bolt shearing failure was observed at the 7.0 mm thick plate. Fig 3 show the load-displacement curves of various specimens. Bolt shearing caused the abrupt reduction of test load at the 6.0 mm and 7.0 mm thick plate before they reached the ultimate state.

The test results for SS490 plate are summarized in Table 8 with the calculation results from equation (2.1). At the plate less than 5.3mm thick, bolt bearing led to increase of test strength in proportion to specimen thickness. However, at the plate over 5.3mm thick, no further increase in the values of strength was provided because their increases were limited by bolt shearing. It is noticeable from Table 8 that the test strength value of 7.0mm thick plate is much less than that of SS400 in Table 7; nonetheless 7.0mm thick specimen of SS400 failed by bolt bearing, while the correspondent SS490 specimen failed by bolt shearing. It is inferred that bolt shearing has a characteristics varied with the strength of plate and more prone to be occurred with high strength steel. Overall, the calculation gives a reasonable estimation of test results in terms of the values of strength as



(a) t=4.5mm, bolt bearing (b) t=5.3mm, bolt bearing



(c) t=6.0mm, bolt shearing & bearing (d) t=7.0mm, bolt shearing

Fig. 2. Failure of bolted seam with a F8.8T bolt for SS490 plate

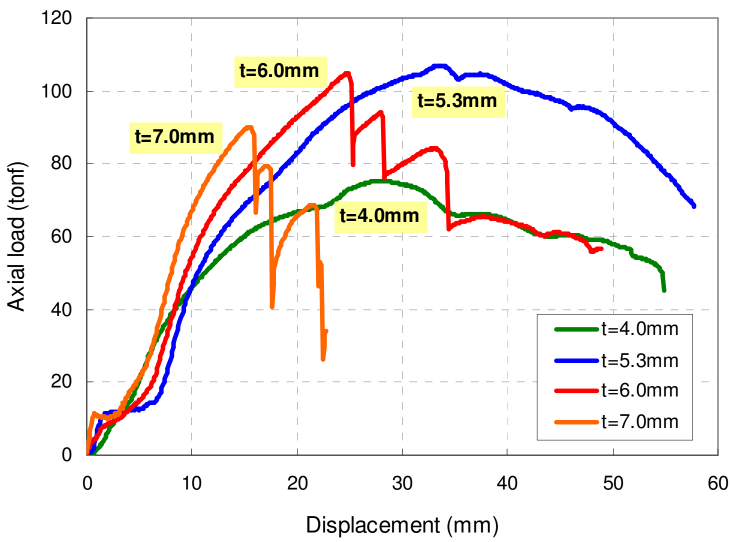


Fig 3. Compressive behaviors of bolted seam with a F8.8T bolt for SS490 plate

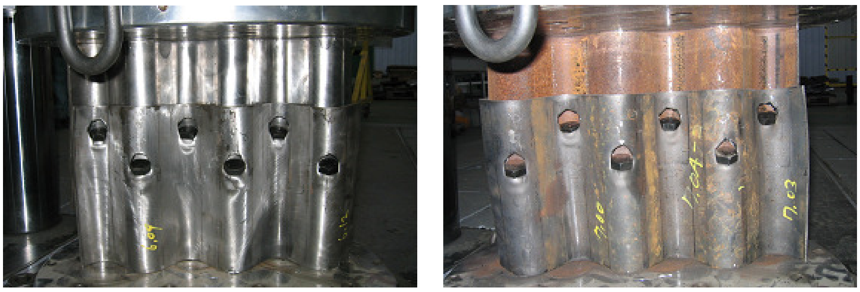
well as failure mode, similarly to calculation for SS400 plate. It seems that the calculation of seam strength by equation (2.1) is reasonable for 2 bolts per corrugation arrangement of 150 by 50mm corrugation.

Table 8. Test and calculation results with a F8.8T bolt for SS490 plate

Nominal thickness (mm)	Test Result		Calculation Result	
	Ultimate Strength (kN/m)	Failure mode	Seam Strength (kN/m)	Failure mode
3.2	1,027	Bolt Bearing	1,171	Bolt Bearing
4.0	1,525		1,463	
4.5	1,837		1,646	
5.3	2,184		1,939	
6.0	2,177	Bolt Bearing + Shearing	2,195	
7.0	1,926	Bolt Shearing	2,248	Bolt Shearing

3.4 Test Results with a F12.9T Bolt

For the 6.0mm and 7.0mm thick plate of SS490, the additional tests were conducted with a F12.9T bolt to induce the bolt bearing failure. As a result, the bolt bearing failure was observed at these plates, as shown in Fig 4, which led to increase in the values of test strength in proportion to specimen thickness over 5.3mm thick. This tendency is well demonstrated in the load-displacement curves in Fig 5 which shows the ultimate state at the 6.0mm and 7.0mm thick plate, differently from Fig 3. The test strength values of 6.0mm and 7.0mm thick plate increased about 20% and 50% by replacing a F8.8T bolt with a F12.9T bolt. Thus, it is noticed that the strength of bolt also should be increased to fully utilize the high strength plate in the bolted seam.



(a) t=6.0mm, bolt bearing (b) t=7.0mm, bolt bearing

Fig 4. Failure of bolted seam with a F12.9T bolt for SS490 plate

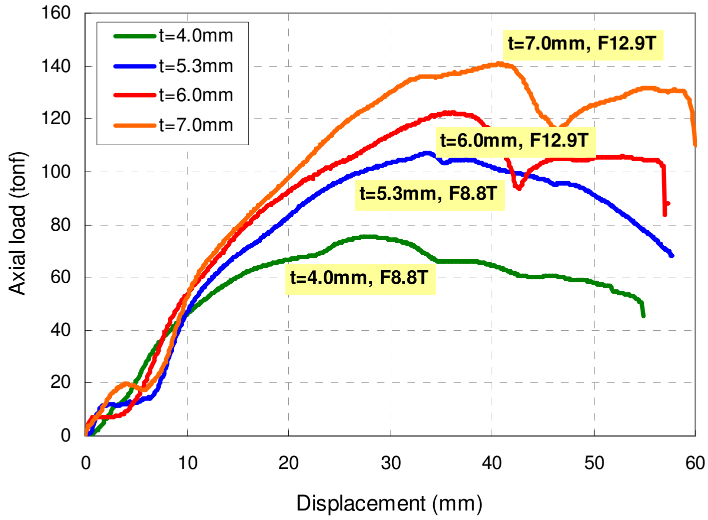


Fig 5. Compressive behaviors of bolted seam for SS490 plate

3.5 Effect of High Stength Steel on Seam Strength

Putting the test results with a F8.8T and F12.9T bolt together, the final values of test strength for SS400 and SS490 plate are compared in Table 9 with their design strength values. The values of test strength increase 11~34% by simply replacing SS400 with SS490 and adopting a 12.9T bolt at the 6.0mm and 7.0mm thick plate. The recommended values of design seam strength for SS490 plate are proposed based on the test results and the normalization to consider the differences in material strength and specimen thickness. The values of design strength of SS490 are about 21~31% greater than those of SS400 specified in ASTM(2003).

Table 9. Seam strength of SS400 and SS490 plate (kN/m)

Nominal thickness (mm)	SS400		SS490	
	Test Strength	Design Strength	Test Strength	Proposed Design Strength
3.2	925*	778	1,027*	979
4.0	1,140*	1,061	1,525*	1,395
4.5	1,507*	1,239	1,837*	1,623
5.3	1,919*	1,522	2,184*	1,939
6.0	2,006*	1,770	2,594**	2,195
7.0	2,582*	2,124	2,870**	2,561

* M20, F8.8T bolt is used

** M20, F12.9T bolt is used

4. BOLTED SEAM TEST FOR 381 BY 140 mm CORRUGATION

4.1 Material Properties

Table 10 shows the yield and tensile strength data of SS490 and SS540 plate before corrugation. The differences in the strength values of two plates are so small that the yield strength and tensile strength of SS540 are only 2% and 8% greater than those of SS490, although the minimum yield and tensile strength of SS540 are about 40% and 10% greater than those of SS490. It seems that SS490 plate has an overestimated material properties compared with other structural steel plates.

Table 10. Coupon test data for 381 by 140mm corrugation plates

	SS490		SS540	
	f_y (MPa)	f_u (MPa)	f_y (MPa)	f_u (MPa)
Test Result	405 ~ 468	512 ~ 566	415 ~ 476	553 ~ 611
Mechanical Requirements	> 285	> 490	> 400	> 540

4.2 Test Program

Similarly to the tests for 150 by 50mm corrugation, the compressive tests on bolted seam were conducted using 10,000 kN capacity UTM, as shown in Fig 6. Differently from the large scale test reported by Roger(2002) which used the 6 pitches specimen with a staggered bolted seam, 2 pitches specimen with a length of 512mm and a width of 838mm was used to conduct a large number of test effectively. As is in the previous tests, a F8.8T bolt of 20mm diameter was used in the first series of test and the additional tests were conducted with a F12.9T bolt of the same diameter.

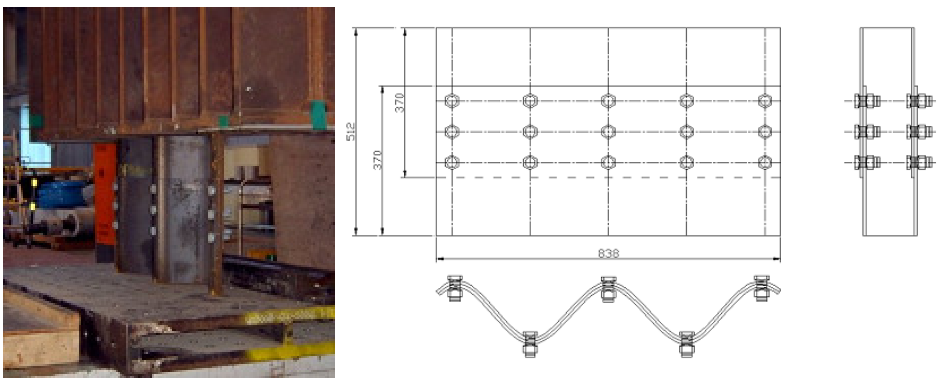


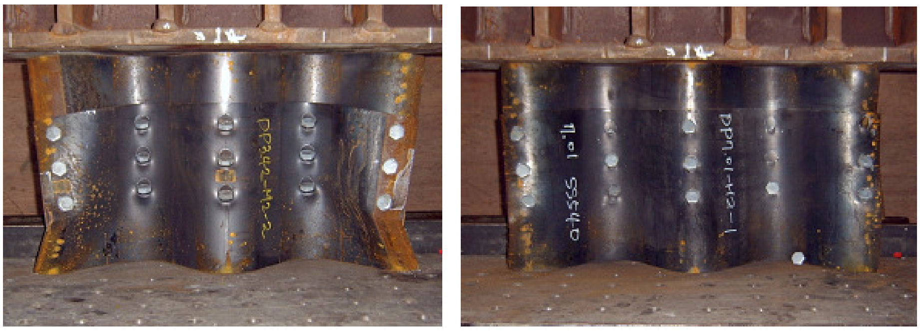
Fig. 6. Test setup and specimen for 381 by 140mm corrugation

4.3 Test Results with a F8.8T Bolt

For SS490 plate, bolt bearing with local buckling along the egde was observed at all the specimens. A representative of this type of failure is shown in Fig 7(a). The test results for SS490 plate are summarized in Table 11 with the calculation results. Differently from the test, the calculation predicts the bolt shearing at the 6.0mm and 7.0 mm thick plate because it overestimates the test strength as much as 35% and gives the bolt bearing strength greater than bolt shearing at these plates.

Table 11. Test and calculation results with a F8.8T bolt for SS490 plate

Nominal thickness (mm)	Test Result		Calculation Result	
	Ultimate Strength (kN/m)	Failure Mode	Seam Strength (kN/m)	Failure Mode
3.42	986	Bolt Bearing	1,482	Bolt Bearing
4.18	1,313		1,811	
5.45	2,031		2,361	
6.23	2,428		2,655	Bolt Shearing
7.01	2,638		2,655	



(a) t=6.23mm(SS490), bolt bearing (b) t=7.01mm(SS540), bolt shearing

Fig 7. Failure of bolted seam with a F8.8T bolt for SS490 and SS540 plate

For SS540 plate, bolt shearing failure was observed at the 7.01mm thick plate, as shown in Fig 5(b), as the values of strength increased about 10% from those of SS490. So, the abrupt reduction of test load was occurred in the load-displacement curves, as shown in Fig 8. The test results are summarized in Table 12 with the calculation results. As is in the SS490 plate, the calculation predicts bolt shearing at the 6.0mm and 7.0mm thick plate because it overestimates the test strength as much as 32%.

Overall, the calculation overestimates the test results more than 30% for 381 by 140mm corrugation. The possible reason for this overestimation is that the calculation assumes a simultaneous bolt bearing failure at all the bolt holes of three row bolted seam and no local buckling of plate at the edge. On the contrary to this assumption, the test showed the gradual bolt bearing failure from the first row to third row and some local buckling at the edge. So, it seems that this calculation method can be useful for one row bolted seam such as 2 bolts per corrugation arrangement of 150 by 50mm corrugation rather than three row bolted seam of 381 by 140mm corrugation.

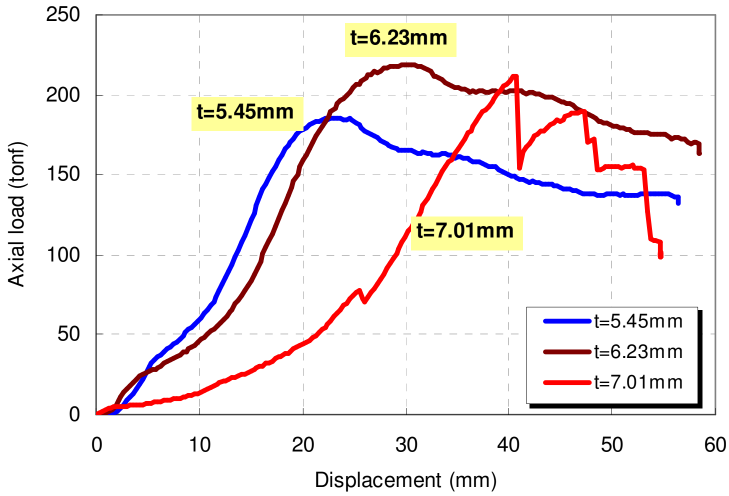


Fig 8. Compressive behaviors of bolted seam with a F8.8T bolt for SS540 plate

Table 12. Test and calculation results with a F8.8T bolt for SS540 plate

Nominal thickness (mm)	Test Result		Calculation Result	
	Ultimate Strength (kN/m)	Failure Mode	Seam Strength (kN/m)	Failure mode
3.42	1,177	Bolt Bearing	1,646	Bolt Bearing
4.18	1,529		2,013	
5.45	2.068		2,624	
6.23	2,508		2,655	Bolt Shearing
7.01	2,487	Bolt Shearing	2,655	

4.4 Test Results with a F12.9T Bolt

For the 7.0mm plate of SS540, the additional tests were conducted with a F12.9T bolt. After all, bolt bearing failure with local buckling at the edge was observed in this test, as shown in Fig 9 and no abrupt reduction of test load was occurred in the load-displacement curves, as shown in Fig 10. The test strength value of 7.01mm thick plate increased about 17% by replacing a F8.8T bolt with a F12.9T bolt.

Fig 9. Failure of bolted seam with a F12.9T bolt for SS540 plate

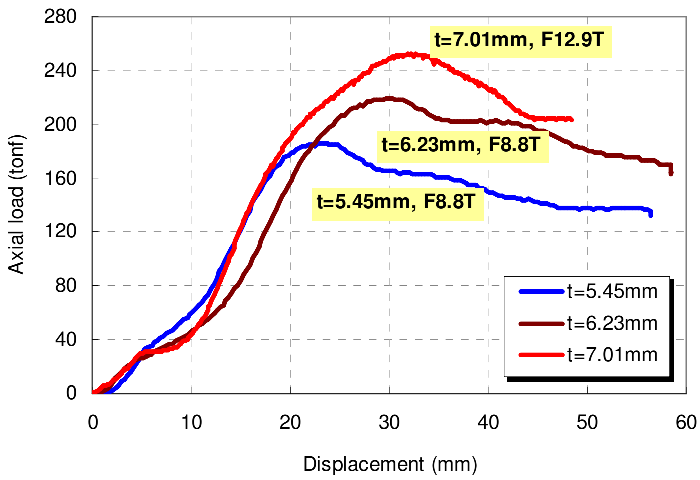


Fig 10. Compressive behaviors of bolted seam for SS540 plate

4.5 Effect of High Stength Steel on Seam Strength

The final values of test strength for SS490 and SS540 plate are shown in Table 13 with their design strength values. The values of test strength increase as much as 2~19% by replacing SS490 with SS540 and adopting a 12.9T bolt at the 7.0mm thick plate, although the yield strength and tensile strength of SS540 are only 2% and 8% greater than those of SS490. Thus, for the validity of these test results, the additional tests using a wide specimen with a staggered bolted seam could be considered in the next project. The recommended values of design seam strength for SS540 plate are proposed based on the test results and the normalization for material strength and specimen thickness. The values of design strength of SS540 are about 8~21% greater than those of SS490 specified in ASTM(2003).

Table 13. Seam strength of SS490 and SS540 plate (kN/m)

Nominal thickness (mm)	SS490		SS540	
	Test Strength	Design Strength	Test Strength	Proposed Design Strength
3.42	986*	884	1,177*	1,073
4.18	1,313*	1,226	1,529*	1,440
5.45	2,031*	1,797	2,068*	1,947
6.23	2,428*	2,101	2,508*	2,356
7.01	2,638*	2,101	2,911**	2,676

* M20, F8.8T bolt is used
** M20, F12.9T bolt is used

5. CONCLUSION

The following conclusions have been drawn from a series of bolted seam test with high strength steel for 150 by 50mm and 381 by 140 corrugation.

(1) For 150 by 50mm corrugation, the values of design seam strength can be increased 21~31% by replacing the steel plate of SS400 with SS490 and adopting a F12.9T bolt for the 6.0mm and 7.0mm thick plate instead of a F8.8T bolt.
(2) For 381 by 140mm corrugation, the values of design seam strength can be increased 8~21% by replacing the steel plate of SS490 with SS540 and adopting a F12.9T bolt for the 7.0mm thick plate instead of a F8.8T bolt. However, the additional tests could be considered for the validity of this result because these increments are too large compared with the increments of material properties.
(3) The calculation method of seam strength comparing bolt bearing and bolt shearing strength can provide a reasonable estimation for 2 bolts per corrugation arrangement of 150 by 50mm corrugation. However, it could overestimate more than 30% for 6 bolts per corrugation arrangement of 381 by 140mm corrugation.

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ABBREVIATION

ASTM : American Standard of Testing ans Materials
JRA : Japanese Road Association
RIST : Research Institute of Science and Technology
JGS : Japanese Geotechnical Society

ZŁĄCZA WYSOKIEJ WYTRZYMAŁOŚCI W KONSTRUKCJACH Z STALOWEJ BLACHY FALISTEJ ZE STALI WYSOKIEJ WYTRZYMAŁOŚCI

Streszczenie

Aby zwiększyć wytrzymałość złącza śrubowego, używane zwyczajowo blachy są zastąpione przez blachy faliste ze stali o wysokiej wytrzymałości o fali 150 na 50 mm oraz 381 na 140mm. Obszerne badania złącza śrubowego zostały przeprowadzone by zbadać efekt blachy ze stali o wysokiej wytrzymałości przy zachowaniu złącza śrubowego. Testy wykazały, że blacha ze stali o wysokiej wytrzymałości spowodowała ścięcie śrub na połączeniu blach przy użyciu relatywnie grubych blach oraz przy ograniczonym wzroście wytrzymałości złącza, w przeciwieństwie do zwyczajowo użytych blach.
W ten sposób zywczajowo użyte złącza zostały zastąpione przez złącza o wysokiej wytrzymałości, co doprowadziło do uszkodznia w skutek utraty nośności przez śruby i wzrostu wytrzymałości tych blach. W rezultacie, założona w projekcie nośność łącza śrubowego może wzrosnąć o 20% przy blachach ze stali o wysokiej wytrzymałości i przystosowaniu śrub o wysokiej wytrzymałości w stosunkowo grubych blachach.