Fracture Mechanics of Concrete Structures
Proceedings FRAMCOS-3
AEDIFICATIO Publishers, D-79104 Freiburg, Germany

EXPERIMENTAL STUDY ON THE MECHANICAL BEHAVIOR IN CONSTRUCTION JOINTS OF CONCRETE STRUCTURES

S. Ishihara
Technical Research Institute, Asanuma Corporation, Japan
H. Mihashi
Dept. of Architecture, Faculty of Engineering, Tohoku University
K. Rokugo
Dept. of Civil Engineering, Faculty of Engineering, Gifu University

Abstract

With the aim of examining shear stress transfer mechanism in construction joints of concrete structures, shear tests which compare the specimens of construction joint having different degrees of roughness with unjointed ones were conducted. As the result, it has become clear that the shear transfer mechanism is subdivided into approximately four stages: before crack initiation, crack propagation stage, transition stage, and interlocking stage, and that the difference of shear transfer between construction joints and unjointed specimens is caused by the difference of behavior in the transition stage. Futhermore, the existence of shear softening in the crack propagation stage was shown by the tests.
Key words: concrete, shear strength, fracture mechanics, shear transfer, shear softening, cracking

1 Introduction

In the 1995 Southern Hyogo Prefecture Earthquake, a lot of unexpected structural damage in concrete structures caused in construction joints were reported. Up to now, the mechanism of shear transfer in construction joints in concrete structures has not been sufficiently clarified. Generally, for improving shear transfer in construction joints, the concrete surface of the joint is roughed. But, the relationship between the degree of roughness of construction joints and shear transfer mechanism is not clear. For the study of shear transfer in construction joints, many shear transfer experiments using pre-cracked concrete blocks and many models which have been proposed to fit those experimental results are instructive. However,those experiments don't show how the surface roughness affects shear transfer. Furthermore, the process of shear tranfer mechanism from crack initiation to aggregate interlocking stage is not clear.

In this paper, we performed shear tests using non pre-cracked concrete specimens of construction joints having different degrees of roughness and unjointed specimens, and those tests were loaded very slowly to observe the process of crack initiation and propagation. As the result, we showed the relationship between degrees of roughness of construction joints and shear transfer behavior, and proposed a fundamental model for shaer transfer mechanism composed of four stages from crack initiation to aggregate interlocking on construction joints and unjointed specimens.

2 Experimental program

2.1 Test specimens

Details of the test specimens used in the pure shear test are given in Table 1. Except for the difference in the degree of roughness of the construction joints, the specimens had the same configuration. The schematic diagrams of test specimens are shown in Fig. 1. The concrete surface of construction joints were roughed with a water jet using high pressure pump. There are three degrees of roughness of construction joint: a little rough, rough, and very rough.

The specimen and loading system of our tests are shown in Fig. 2. The shear plane of all the specimens was $100\text{cm}^2(10\times10\text{cm})$ in the area. When loaded as indicated by the arrow, shear without moment is produced in the shear plane.

Table 1. Details of specimen

Series	Type of Const.Joint	Degree of Roughness of Const.Joint	Numbers
A	Const.joint-UP (Upper)	A little rough	2
		Rough	3
		Very rough	3
B	Const.joint-LW (Lower)	Rough	3
		Very rough	2
C	Unjointed	-	3

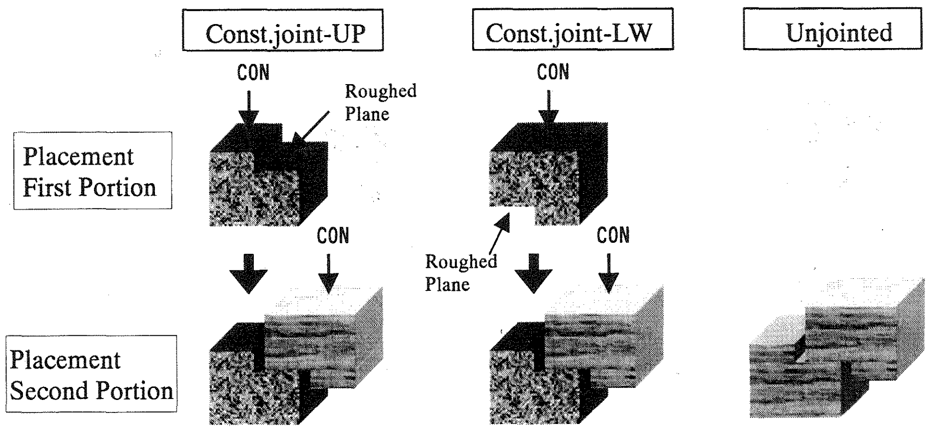


Fig. 1. Schematic diagram of test specimens

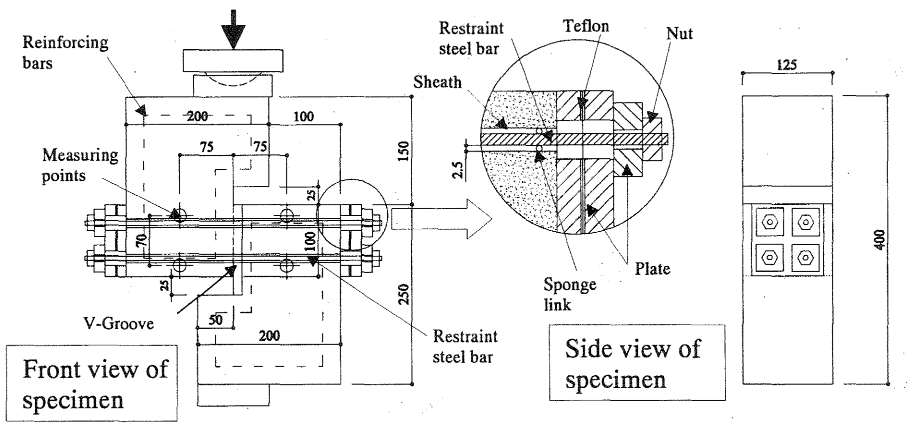


Fig. 2. Specimen and loading system

Instead of embedded reinforcing bars, four internal restraint steel bars passing through the inner sheaths are provided to apply the axial compressive force upon a crack plane by pushing. At the start of the shear test, the internal restraint steel bars had no applied axial compressive force. Dowel action and unnecessary shear resistance due to the internal restraint steel bars were avoided by making the sheaths 5mm larger in the diameter and placing the bars in the center. The reinforcement ratio of restraint steel bars was 1.34 percent.

2.2 Concrete

The Mix proportion of concrete is given in Table 2. 6 days after placing concrete in the first portion, the joint surface was roughed with a water jet. 7 days after roughing , the second portion was placed. Unjointed concrete specimens were placed at the same time as the second portion. The material properties of the concrete are shown in Table 3.

Table 2. Mix proportion of concrete

Type of Cement	G_{max} (mm)	Unit content (kg/m^3)				Chemical Admixture (ℓ/m^3)
		Cement	Water	Fine Aggregate	Coarse Aggregate	
NPC*	15	315	189	808	949	0.788

*NPC=Normal Portland Cement

Table 3. Material properties of concrete

	Compressive Strength (N/mm^2)	Tensile Strength (N/mm^2)	Young 's Modulus ($\times 10^4$N/mm^2)
First Portion	24.2	2.07	2.3
Second Portion	24.2	2.04	2.32
Unjointed	24.2	2.04	2.32

2.3 Measuring of concrete surface roughness

The concrete surface roughness of the concrete joints was measured at intervals of about 0.1mm using a laser displacement guage connected to a computer. The method of measuring the concrete surface is shown in Fig. 3. Definition of concrete surface roughness (Ra) is shown in Fig. 4.

2.4 Testing procedure

The shear displacement rate was 0.02mm/min. After passing the peak of the load-shear displacement curve, the displacement rate was increased to 0.06 mm/min. The tests were ended when the shear displacement had reached a value of 2.0 mm. The shear displacement and crack width were measured on each side of the specimen with tranducers.

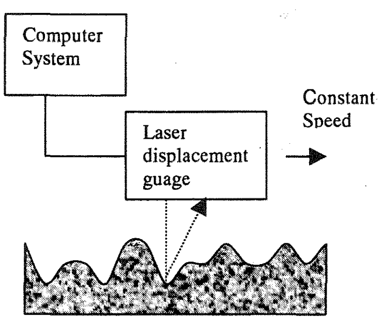
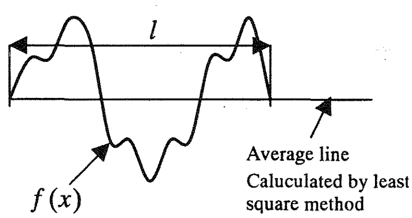


Fig. 3. Method of measuring concrete surface



$$R_a = \frac{1}{l}\int_0^l |f(x)|dx$$

Fig. 4. Definition of concrete surface roughness (Ra)

3 Experimental results and discussion

3.1 Relation between shear stress and shear displacement

Relation between shear stress and shear displacement for representative specimens in Table 4 are shown in Fig. 5. Each specimen showed phased change. A schematic description of the phased changes in shear stress and shear displacement is shown in Fig.6. The phased change were subdivied into approximately four stages. The first was the stage before crack initiation which showed elastic behavior, the second was the stage of crack propagation, the third was a transition stage after finishing crack propagation, and the final stage was stable aggregate interlocking stage. The most distinguished difference among these results was the behavior after the start of transition. The shear displacement in the transition stage of construction joint specimens was larger than that of unjointed specimens. Also, the rougher the surface roughness of the construction joints, the less the shear displacement in the transition stage.

Table 4. Test results for representative specimens

Specimen	Type of Joint	Ra (mm)	τ_{ci} (N/mm^2)	τ_{si} (N/mm^2)	τ_{si} / τ_{ci} (%)
1	Const.joint-UP	0.61	4.42	0.93	21.0
2	Const.joint-UP	2.19	4.73	3.16	66.8
3	Unjointed	-	4.43	3.36	75.9

τ_{ci}: shear stress at cracking initiation

τ_{si}: shear stress at the start of interlocking stage

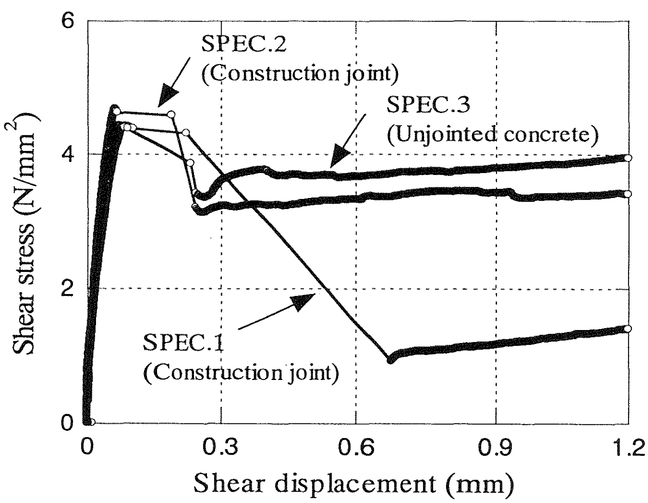


Fig. 5. Shear stress vs. shear displacement of representative specimens

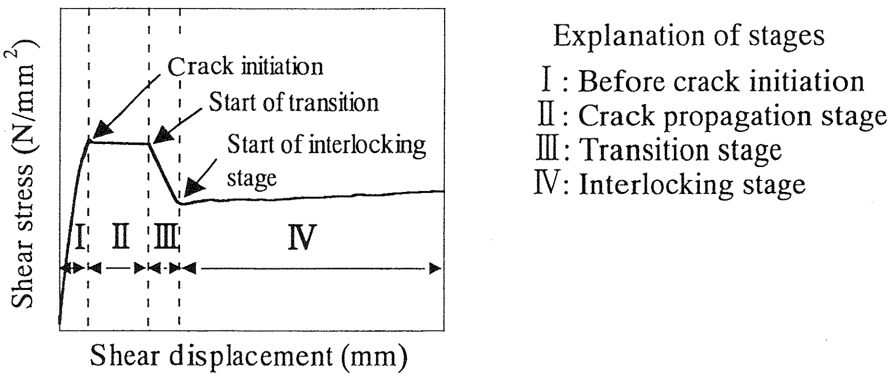


Fig. 6. Schematic description of shear stress and shear displacement

3.2 Relation between shear stress and concrete surface roughness

Relation between shear stress at cracking initiation τ_{ci} and concrete surface roughness Ra of construction joints for each specimen are shown in Fig. 7. The shear stress in construction joints at crack initiation was almost constant although degrees of concrete surface roughness was different. Also the shear strength of specimens with construction joints was nearly the same as that of unjointed specimens. Furthermore, there was no difference between Const.joint-UP and Const.joint-LW . That the shear stress at crack initiation depends on the mortar matrix is thought to be the reason for these phenomena. Relation betweeen shear stress at the start of interlocking stage τ_{si} and concrete surface roughness Ra of construction joints for each specimen is shown in Fig. 8. The τ_{si} / τ_{ci} vs. concrete surface roughness Ra of construction joints relation for each specimen is shown in Fig. 9. A high correlation was recognized between the shear stress at crack initiation, τ_{si} / τ_{ci} and the surface roughness of the construction joints. To have the same capacity as unjointed specimens, it is to be noted that Ra needs to be at least 1.5mm. Consequently, the difference of shear stress owing to surface roughness degrees was revealed in the stage after crack initiation.

3.3 Mechanism of shear crack propagation

Relation between crack width and shear displacement after crack initiation are shown in Fig. 10. In this experiment, the stage in which shear cracks propagated after crack initiation was confirmed. In this stage two mechanisms may overlap: one is "shear softening" in which shear stress along the crack acts in the direction normal to the point of shear cracking line, the other is "shear transfer" due to aggregate bridging. Because the crack width in the crack propagation stage is very small though it may depend on the maximum aggregate size, shear transfer in this stage is governed not by the magnitude of crack width but by the

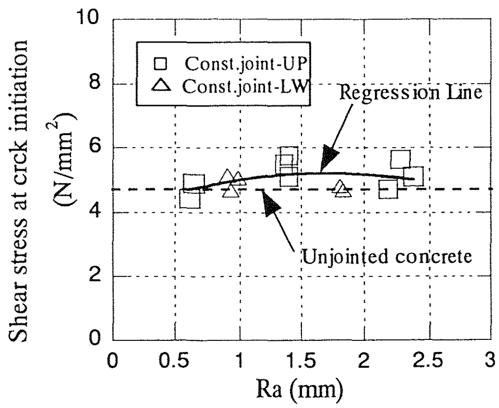


Fig. 7.
Shear stress at crack initiation τ_{ci} vs. concrete surface roughness Ra of construction joint

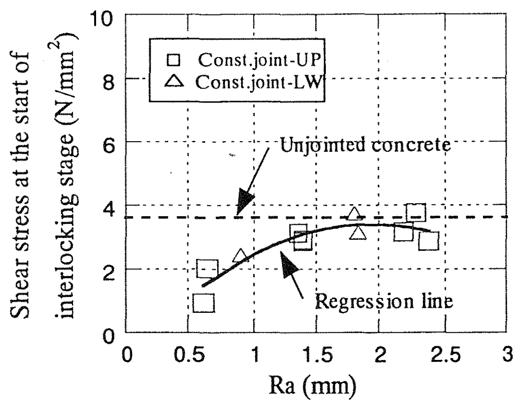


Fig. 8.
Shear stress at the start of interlocking stage τ_{si} vs. concrete surface roughness Ra of construction joint

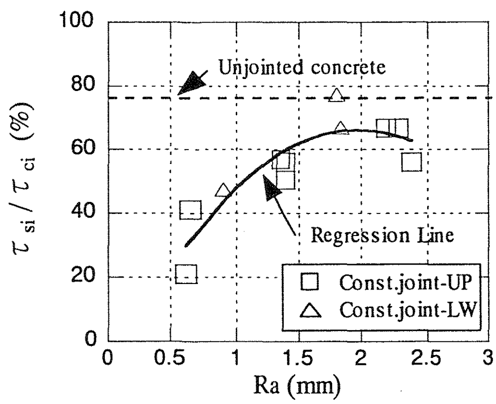


Fig. 9.
τ_{si} / τ_{ci} vs. concrete surface roughness Ra of construction joint

ratio of shear displacement to crack width. Thus, the model proposed by Okamura and Maekawa (1991) was adopted as the model for shear transfer. The model is described with eq.(1) in Table 5. The following two assumptions were introduced to adopt this model.

1) Shear transfer starts from crack initiation and shear stress by shear transfer reaches the maximum value at the end of crack propagation.

2) Crack width and shear displacement change proportionally within the interval of data at crack initiation and at the end of crack propagation.

The coefficient m_1 of this model is related to contact density and contact area of the crack surface. According to the assumption 1), the coefficient was determined as to match with shear test results. The analytical results of shear transfer by this model are shown in Fig. 11(a)～(c). The difference between measured total shear stress and the analytical results of shear transfer could be caused by shear softening. In other words, it is supposed that the shear softening and shear transfer occur simultaneously just after crack initiation.

After crack propagation ends, the total mechanism enters into another new equilibrium system. In the transition stage, unjointed specimens display less shear displacement compared with construction joints. This phenomenon may be caused by the following mechanism: the weaker the supporting matrix strength of construction joints than that of unjointed specimens, the more the matrix supporting interlocking aggregates yields as shown in Fig. 11(d). Furthermore, the less the surface roughness of the construction joints, the larger shear displacement was in the transition stage. That was because the less the surface roughness of the construction joints, the less the surface roughness of the crack surface, and the aggregates did not interlock effectively when the crack width increased.

In the new equilibrium system, aggregates interlocked stably. This interlocking has the same shear transfer mechanism as many previous shear experiments using pre-cracked concrete blocks. A model for the interlocking shear transfer is described with eq.(2) in Table 5. The coefficient m_2 of this equation was determined according to experimental results. The analytical results of interlocking transfer calculated by this model is shown in Fig.11(a)～(c). The hatched area in Fig. 11 is the transition zone.

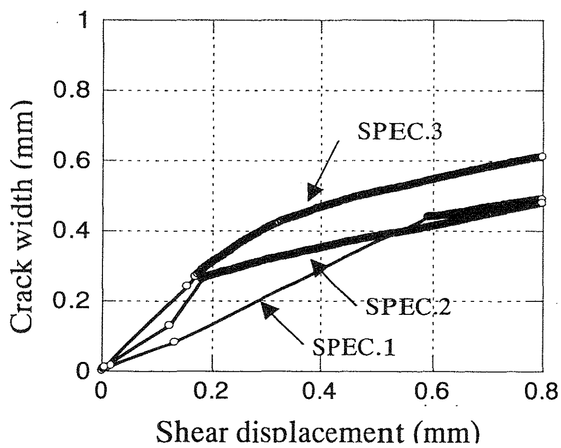


Fig. 10. Crack width vs. shear displacement after crack initiation

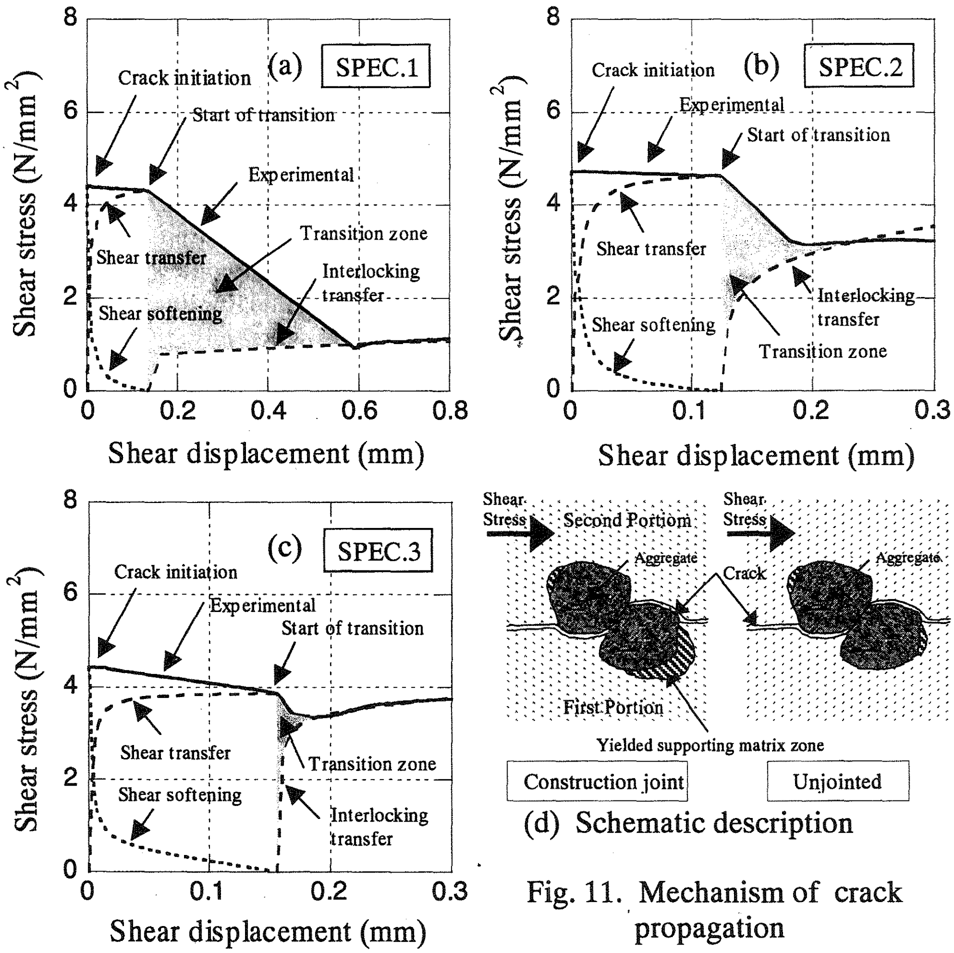


Fig. 11. Mechanism of crack propagation

Table 5. Model for shear transfer and interlocking stage

(A) Mode of shear transfer	(B) Mode of interlocking
$$\tau = \frac{m_1 \psi^2}{1+\psi^2} \quad (1)$$ where $\psi = \delta / \omega$ δ : Shear displacement ω: Crack width fc: Compressive strength $m_1 = 2.055\ fc^{1/3}$ (SPEC.1) $3.326\ fc^{1/3}$ (SPEC.2) $4.555\ fc^{1/3}$ (SPEC.3)	$$\tau = \frac{m_2 \phi^{3/5}}{1+\phi^{3/5}} \quad (2)$$ where $\phi = \delta / \omega(\delta)$ δ : Shear displacement $\omega(\delta)$: Crack width fc: Compressive strength $m_2 = 0.65\ fc^{1/3}$ (SPEC.1) $2.5\ fc^{1/3}$ (SPEC.2) $2.7\ fc^{1/3}$ (SPEC.3)

4. Conclusions

To examine shear stress transfer mechanism in construction joints of concrete structures, the shear tests to compare specimens of construction joint having different degrees of roughness with ones unjointed were carried out. The following conclusions were obtained.

1. The shear transfer mechanism is subdivided into approximately four stages. The first was the stage before crack initiation which showed elastic behavior, the second was the stage of crack propagation, the third was the transition stage after finishing crack propagation, and the final was the interlocking stage.
2. In the crack propagation stage, two mechanisms overlap. One mechanism is "shear softening" in which shear stress along the crack acts in the direction normal to the point of shear cracking line. Another mechanism is "shear transfer" of aggregate bridging.
3. The shear stress of construction joints at crack initiation was almost constant although degrees of concrete surface roughness was different. Also the shear strength of specimens with construction joints at crack initiation was nearly the same as that of unjointed specimens. The difference in shear transfer between construction joints and unjointed specimens or by degrees of surface roughness of construction joints is caused by the difference of behavoir in the transition stage.

5 References

Bazant, Z.P. and Gambarova, P. (1980) Rough cracks in reinforced concrete, **Journal of the Structural Division,** ASCE, ST 4 (4), 819-842.

Li, B. and Maekawa, K. (1988) Stress transfer constitutive equation for cracked plane density function, **Concrete Journal**, JCI, 26 (1), 123-137 (in Japanese).

Mihashi, H. (1996) State-of-the-art report on fracture mechanics applied to reinforced concrete structures. **Concrete Journal of JCI**, 34 (5), 5-15 (in Japanese).

Okamura, H. and Maekawa, K. (1991) Nonlinear analysis and constitutive models of reinforced concrete, Giho-do Shuppan Co. Ltd. ,Tokyo, Japan.

Shirai, N. , Moriizumi, K. and Ishii, K. (1995) Size effect on shear strength in reinforced concrete beams with shear reinforcement. **Fracture Mechanics of Concrete Structures** (ed. F.H.Wittmann), Aedificatio Publishers, 645-654.

Walraven, J.C. and Reinhardt, H.W. (1981) Theory and experiments on the mechanical behavior of cracks in plain and reinforced concrete subjected to shear loading. **HERON,** 26, 1A.