Bonding between New and Old Concrete in Composite Beams under the Effect of Static Loads

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ABSTRACT

This study experimentally investigates the bonding strength of aged and other forms of new concrete. Its primary objective is to assess several methodologies for achieving effective bonding behavior. Additionally, the present study examines the impact of varying stiffness and shrinkage rates at the boundary between concrete layers poured at different times. The experiment on bonding strength included examining the effects of several factors, such as surface preparation, bonding agent type, age difference, and the type of concrete used in the new layer. The flexural test results show that the ultimate load decreases by 16.2%, and 13.3% for composite beams with new concrete of Self-Comparing Concrete (SCC), and steel fibers, respectively, compared to the reference beam. However, the ultimate load increases by 6.5% and 9% for composite beams with new concrete of Sika and High-Strength Concrete (HSC), respectively, compared to the reference beam. So, using new concrete with Sika or HSC is the best choice. The composite beam with shear connectors has the highest ultimate load in the test, whereas the beam with SCC as a new layer has the lowest value.

Keywords-composite beams; new concrete; static loads; old concrete; SIKA; SCC

I. INTRODUCTION

The bonding between preexisting and newly poured concrete is a vital element in the restoration process. Several studies have focused on the use of conventional vibrated concrete in both original and overlay concrete scenarios. However, there is a lack of information on the behavioral traits of different types of recently created concrete, especially when it comes to overlay concrete [1-4]. The maintenance system may have been seen as a complex system including three separate phases: the substrate, overlay, and zone of bonding. The phrase zone of bonding denotes the area including and incorporating the bond plane. The bond area must have sufficient structural integrity to withstand the different external pressures applied to the system. Several factors impact the robustness and durability of a link. To guarantee the quality assurance of bond strength, it is essential to use testing methodologies that can precisely quantify the bond strength while also being capable of identifying the exact failure mechanism. Several investigations have been performed, leading to the development of different testing protocols. The choice of a suitable test depends on the applied forces and the manner of failure in each specific case. Tests are often conducted in both laboratory and site settings [5]. The bond strength pertains to the level of adhesion between the overlay and substrate, and it has the capacity to be the most susceptible feature of the system. A robust connection is an essential factor in the formation of a cohesive system [6-9]. The main determinants influencing the strength of interfacial bonds are curing conditions, water-to-cement ratio, surface roughness, age disparity between concrete layers, supplemental cementitious materials, and the kind of bonding agent. The primary techniques for connecting old and new concrete layers include enhancing the roughness of the substrate surface, using bonding chemicals, and utilizing nails [10-12]. Authors in [13] examined how interface treatment affects seismic performance of columns enhanced with Reinforced Concrete (RC) jacketing to improve the bending moment at the ultimate stage. A numerical analysis was undertaken to better understand the topic. For undamaged samples with a bending moment/shear force ratio bigger than 1.0%, casting an RC jacket with a thickness less than 17.5% of the column width is sufficient to achieve the monolithic behavior of the composite element. Authors in [14] conducted experimental research on the bond properties of High-Early-Strength engineered Cementitious Composites (HES-ECC), which exhibit good ductility and minimal early-age shrinkage. To evaluate bonding performance, a commercially available repair material (REP) that is often used for rapid and durable infrastructure repairs was employed. Bond properties were evaluated using slant shear and tensile pull-off tests. This research examines how compressive strength and autogenous shrinkage affect individual bond strength values, as well as the mechanical characteristics of the suggested materials. Experimental findings show that the impact of compressive strength and autogenous shrinkage on bond strength differs /in terms of the test technique deployed. Using HES-ECC mixes greatly enhances the bond properties of a repair assembly compared to REP. In direct pull-off testing, HES-ECC combinations outperform REP in terms of bond strength and failure type.

Authors in [15] evaluated the flexural strength of beams made of regular concrete and retrofitted with high strength concrete. The rough interfacial surface of a beam was prepared using a variety of techniques, including sandblasting, drilling, grooves, and steel brushing, to strengthen the binding between the two concrete halves of the beam. It was found that sand blasting on the interfacial surface of beams results in great flexural toughness and less breaking during collapse. Authors in [16] carried out an experimental investigation to study the interfacial fracture toughness of new-to-old concrete systems. They also examined the impact of Shrinkage Reduction Admixture (SRA) on the interface integrity of such systems. The findings demonstrated that incorporating SRA into the new concrete mixing design enhanced the interface fracture toughness of the new-to-old concrete systems. Furthermore, during SRA incorporation into the mixing design, the rate at which interface fracture toughness decreased when the samples were subjected to moisture conditions was likewise reduced, suggesting that the new-to-old system is more resilient under moisture circumstances. Authors in [17] investigated the shrinkage and bonding characteristics of concrete beams repaired with Strain-Hardening Cement-based Composites (SHCC). Their findings exhibit that the SHCC repair layer develops many tiny cracks rather than local fractures under shrinkage stress, effectively managing interfacial delamination. The primary factor influencing the shrinkage and deformation coordination of beams with SHCC repairs is the interfacial bonding quality. The SHCC repair layer's crack width is comparable when the interface roughness varies.

II. RESEARCH SIGNIFICANCE

The primary goal of this study is to experimentally investigate the bonding between new and old concrete in composite beams under the effect of static loads in an attempt to assess several strategies for ensuring homogenous behavior and strong bonds. The present study evaluates the impact of varying stiffness and shrinkage at the interface between concrete layers that were cast at distinct ages. Studying the effects of numerous variables, including surface preparation, bonding agent type, age difference, and new concrete type, was the focus of the bonding strength experiment.

III. EXPRIMENTAL PROGRAM AND MATERIAL PROPERTIES

The experimental work for structural behavior consists of casting and testing 13 composite beams under the effect of static loads. The 13 beams were divided into many groups according to surface preparation, bonding agent, strength of the new concrete, amount of steel reinforcement crossing the interface, age of the old concrete, and type of new concrete, as shown in table I. All composite beams have the same length, width, height, and reinforcement, as evidenced in Figure 1. Using plastic spacers, a 25 mm transparent cover was added to each side of the produced reinforcing steel cages. The surfaces of the RC beams were wire-brushed to provide a rough surface for rough groupings before fresh concrete was poured over the old concrete surfaces. The following day, the bases received an 1-2 mm layer of adhesive. Then the overlay was cast. Figures 1-4 portray the steps of production of the composite beams. All experimental work was carried out in the Civil Engineering Department Laboratory- Engineering college – University of Basrah.

TABLE I. DATA OF THE COMPOSITE BEAMS' SPECIMENS

Group	Beam ID	Bonding agent	Age of old concrete	Type of surface	Type of new concrete
Homogeneous	BS	-	> 1 year	-	One unit
Shear connectors	BS-SH	-	> 1 year	smooth	Same old layer
Age of old concrete	BS-3D	-	3 days	smooth	Same old layer
	BS-7D	-	7 days	smooth	Same old layer
	BS-28D	-	28 days	smooth	Same old layer
	BS-1Y	-	1 year	smooth	Same old layer
Type of new concrete	BS-SIKA	-	> 1 year	smooth	SIKA
	BS-SCC	-	> 1 year	smooth	SCC
	BS-SF	-	> 1 year	smooth	Steel fibers
	BS-HSC	-	> 1 year	smooth	HSC
Surface preparation	BS-RO	-	> 1 year	rough	Same old layer
Type of bonding agent	BS-SBR	SBR	> 1 year	smooth	Same old layer
	BS-EP	epoxy	> 1 year	smooth	Same old layer

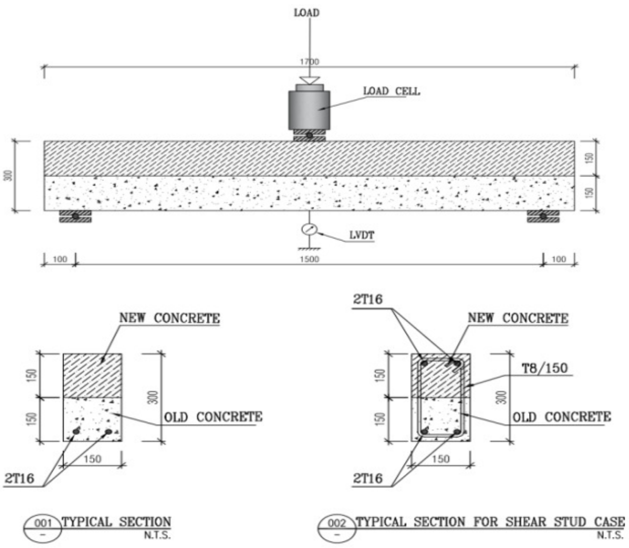

Fig. 1. Details of composite beams.

Fig. 2. The wooden mold and reinforcing steel cage for composite beams.

Fig. 3. Producing composite beam (a- Apply the adhesive to the old concrete, and b- Pouring the new concrete layer).

Fig. 4. Composite beams test setup.

IV. TEST RESULTS

The results of 13 composite beams loaded by static loads using several techniques to study the bonding between old and new concrete in beams are presented in this section.

A. *Deformability of the Examined Beams*

Deformability encompasses several aspects, including the strain shown by a body, the curvature seen in a section, the rotation experienced by a member, and the deflection encountered by a member. This section discusses the correlations between the applied load and mid-span deflection for all composite beams. The serviceability limit used for the study was determined by dividing the experimental ultimate load by a factor of 1.7, a recommendation supported by other researchers such as those in [18]. This limit was established based on the absence of any unwanted cracking or deformation detected at this load level. Consequently, Table II provides a comprehensive overview of the pertinent mid-span deflections pertaining to the loading stages of service and ultimate applied load. The initial deflection of each sample exhibits a linear relationship. Following the application of a cracking load, the examined samples demonstrated deflection patterns that displayed a semi-linear relationship with the applied load. However, it is noteworthy that the inclination of these deflection lines was significantly less steep compared to the pre-cracking load condition. Furthermore, the deflection curves diverged based on the degree of cracking and the subsequent reduction in stiffness. The inclination of the linear segment varies among the specimens belonging to each group. Once the loads approach the ultimate load, the tested samples manifest a non-linear deflection pattern in relation to the applied load. Table II shows that, at service stage the deflection of mid the span decreases from 22% to 67% for all beams except for the beam with shear connectors, where deflection increased by 90%. This occurred since the ultimate load of this beam is relatively large, and therefore the service load will be large as well.

TABLE II. LOAD AND THE CORRESPONDING DEFLECTION FOR BEAMS AT DIFFERENT LOADING STAGES

Beam ID	At service loading Ps		At ultimate load		Failure load P_{ult}(kN)
	Deflection (mm)	Decrease percentage (%)	Deflection (mm)	Decrease percentage (%)	
BS	3.08	Ref.	4.29	Ref.	78.9
BS-SH	5.85	90 (increasing)	28.3	556 (increasing)	178.4
BS-3D	2.35	24	4.2	2.1	65.6
BS-7D	1.26	59	2.35	45.2	43.1
BS-28D	1.02	67	2.26	47.3	40.6
BS-1Y	1.39	55	2.45	43	39.2
BS-SIKA	2.31	25	4.5	4.9 (increasing)	84
BS-SCC	1.94	37	3.38	21.2	66.1
BS-SF	2.07	33	3.82	11	68.4
BS-RO	2.41	22	4.37	1.9 (increasing)	77.5
BS-SBR	2.07	33	4.18	2.6	70.3
BS-EP	2.34	24	4.17	2.8	73.6
BS-HSC	2.05	33.4	4.18	2.6	86

1) *Effect of the Age of Old Concrete*

Four ages were used for the old concrete of the beams (3days, 7days, 28 days, and one year) and their results were compared with the reference sample. Figure 5 displays the load-deflection curves of this group. Table III demonstrates that, at service load the deflection of the middle span decreases from 24% to 67% for all beams of this group. While at the ultimate stage the deflection of the mid span decreases from 2.1% to 47.3% for all beams of this group. Figure 5 depicts the effect of the age of the old concrete on the load-deflection curves of the static group. It is noted that as the age of the old concrete increases, the bond between the old and new concrete decreases, but the strength of the old concrete increases, which leads to the stiffness and load-bearing capacity of the composite beam increasing significantly at the age of one year, with the results varying for other ages.

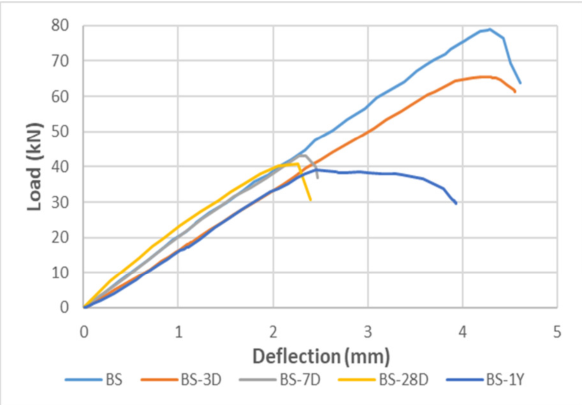

Fig. 5. Effect of old concrete age on the load-deflection curves.

TABLE III. LOAD AND THE CORRESPONDING DEFLECTION FOR BEAMS (AGE OF OLD CONCRETE)

Beam ID	At service loading Ps kN		At ultimate load		Failure load P_{ult} (kN)
	Deflection (mm)	Decrease percentage (%)	Deflection (mm)	Decrease percentage (%)	
BS	3.08	Ref.	4.29	Ref.	78.9
BS-3D	2.35	24	4.2	2.1	65.6
BS-7D	1.26	59	2.35	45.2	43.1
BS-28D	1.02	67	2.26	47.3	40.6
BS-1Y	1.39	55	2.45	43	39.2

2) Effect of the Type of New Concrete

Four types were used for the new concrete of the beams (Sika, SCC, concrete with steel fibers, and HSC) and their results were compared with the reference beam. Figure 6 presents the load-deflection curves of this group. Table IV demonstrates that, at service stage the deflection of the mid span decreases by 25%, 37%, 33%, and 33.4% for the composite beam with Sika, SCC, concrete with steel fibers, and HSC, respectively, with respect to the reference beam. While at the ultimate stage the deflection of the mid span decreases by 21.2%, 11%, 2.6% for the composite beam with SCC, concrete with steel fibers, and HSC, respectively, with respect to the reference beam. However, the deflection of the mid span increases by 4.9% for the composite beam with Sika, which means that the last type gives strong bonding. Figure 6 shows the effect of the type of new concrete on the load-deflection curves of the static group. It is noted that the beams with sika or HSC had the highest bonding and strength, which led to their ultimate load and stiffness being the highest in this group.

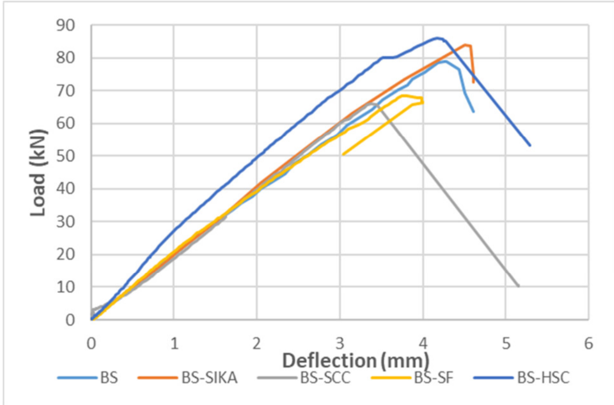

Fig. 6. Effect of the type of new concrete on the load-deflection curves.

TABLE IV. .LOAD AND THE CORRESPONDING DEFLECTION FOR BEAMS OF STATIC LOAD (TYPE OF NEW CONCRETE

Beam ID	At service loading Ps kN		At ultimate load		Failure load P_{ult} (kN)
	Deflection (mm)	Decrease percentage (%)	Deflection (mm)	Decrease percentage (%)	
BS	3.08	Ref.	4.29	Ref.	78.9
BS-SIKA	2.31	25	4.5	4.9 (increasing)	84
BS-SCC	1.94	37	3.38	21.2	66.1
BS-SF	2.07	33	3.82	11	68.4
BS-HSC	2.05	33.4	4.18	2.6	86

3) Effect of the Type of Bonding Agent

Two types were utilized for the bonding agent of the composite beams (epoxy and SBR), and then their results were compared with the reference sample. Figure 8 displays the load-deflection curves of this group. Table V showcases that, at service load the deflection of the middle span decreases by 33% and 24% for the composite beam with SBR, and epoxy, respectively, compared to the reference beam. While at the ultimate stage the deflection of the mid span decreases by 2.6% and 2.8% for the composite beam with SBR and epoxy, accordingly, with respect to the reference sample.

TABLE V. LOAD VS. DEFLECTIONS FOR BEAMS OF STATIC LOAD GROUP (TYPE OF BONDING AGENT)

Beam ID	At service loading Ps kN		At ultimate load		Failure load P_{ult}, (kN)
	Deflection (mm)	Decrease percentage (%)	Deflection (mm)	Decrease percentage (%)	
BS	3.08	Ref.	4.29	Ref.	78.9
BS-SBR	2.07	33	4.18	2.6	70.3
BS-EP	2.34	24	4.17	2.8	73.6

Figure 7 exhibits the impact of the type of the bonding agent on the load-deflection curves of the static group. It is noted that the two agents had approximately the same effect on the ultimate load and stiffness of the composite beams.

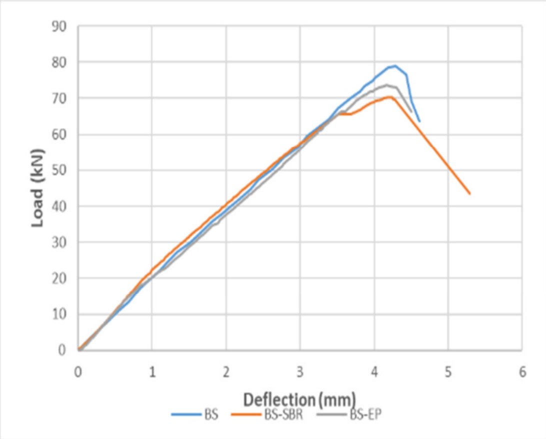

Fig. 7. Effect of the type bonding agent on the load-deflection curves.

4) *Effect of the Type of Bonding Method and Surface Roughness*

Two types were utilized for this group of the composite beams (old concrete with roughness surface and old concrete with stirrups as shear connectors). Then their results were compared with the reference beam. Figure 8 shows the load-deflection curves of this group. Table VI indicates that, at service load the deflection of the middle span increases by 90% for the composite beam with shear connectors, but decreases by 22% for the composite beam with rough surface. While at the ultimate stage, the deflection of the mid span increases by 1.9% for the composite beam with shear connectors and with rough surface, correspondingly, regarding the reference beam. Figure 9 portrays the effect of the type of bonding method and surface roughness on the load-deflection curves of the static group. It is noted that the beam with shear connectors had a significant effect on the ultimate load and stiffness of the composite beams. However, the beam with rough surface had a small effect on the ultimate load and stiffness of the composite beams. It is very clear that the shear connectors greatly increase the bond strength.

TABLE VI. OAD VS. DEFLECTIONS FOR BEAMS (TYPE OF BONDING METHOD AND SURFACE ROUGHNESS)

Beam ID	At service loading Ps kN		At ultimate load		Failure load P_{ult}, (kN)
	Deflection (mm)	Change percentage (%)	Deflection (mm)	Increase percentage (%)	
BS	3.08	Ref.	4.29	Ref.	78.9
BS-SH	5.85	90 (increasing)	28.3	556	178.4
BS-RO	2.41	22 (decreasing)	4.37	1.9	77.5

B. *Load-Carrying Capacity and Failure Mode for the Static Load Group*

In this study, the failure load was operationally defined as the maximum load at which the beam demonstrated a significant decrease in strength and finally underwent structural collapse. It is worth noting that the beams only exhibit flexural cracks. When subjected to significant loads, the occurrence of substantial flexural stresses in the central region of a span leads to the development of vertical flexural fractures in the highly resilient fibers located towards the bottom of the section, particularly near the area experiencing the highest bending moment. With an increase in stress, there is a notable increase in the quantity of vertical flexural cracks, as well as their length, the inclination of their terminations, and the extent of flattening seen in the flexural-shear cracks. The inclined cracks have been seen to occur due to the application of a load.

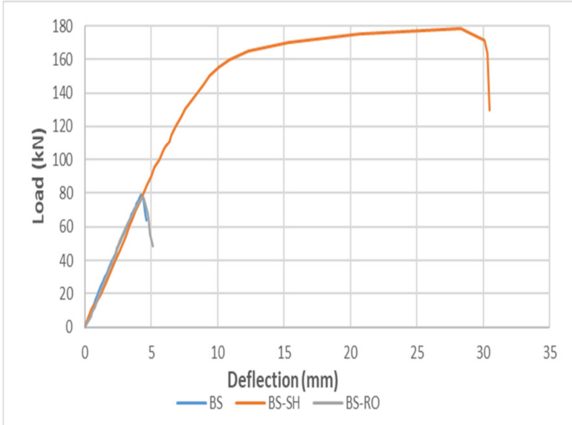

Fig. 8. Effect of the type of bonding method and surface roughness on the load-deflection curves.

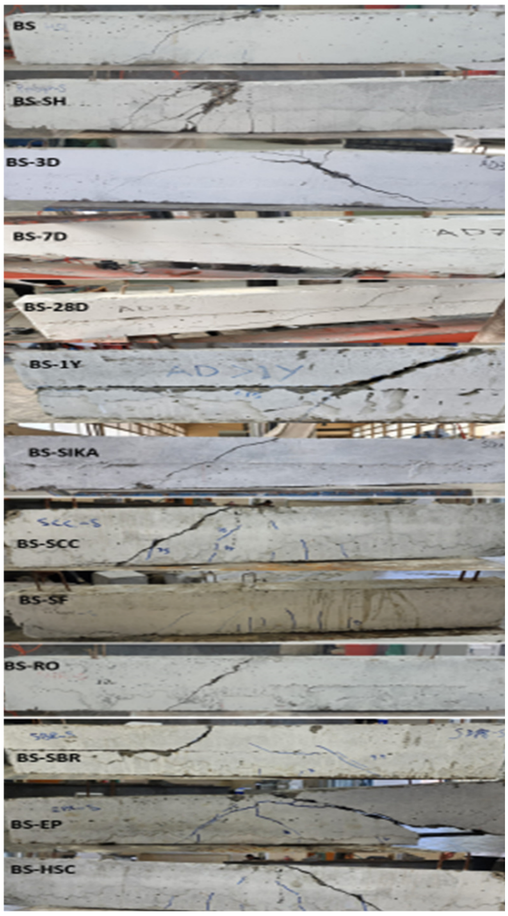

Fig. 9. Failure modes of beams under static loads.

Figure 9 illustrates that all tested beams failed by shear with diagonal tensile fracture except the beam of old concrete with an age of 7 days and the beam with the agent SBR. In contrast, the last two beams failed by shear with a diagonal tensile fracture at the upper part (new layer) followed by separation between the two layers.

1) Effect of the Age of Old Concrete

Four ages were used for the old concrete of the beams (3days, 7days, 28 days, and one year). Then their results were compared to the reference beam. According to the data shown in Table VII, increasing the age of the old concrete results in a corresponding decrease of the ultimate strength of the beam. The ultimate load decreases by 16.9%, 45.4%, 48.5%, and 50.3% for the composite beam with old concrete with an age of 3 days, 7 days, 28 days, and one year, respectively, regarding the reference beam.

TABLE VII. ULTIMATE LOAD FOR BEAMS (AGE OF OLD CONCRETE)

Beam ID	Failure load P_u,(kN)	Decrease Percentage in P_u (%)
BS	78.9	Ref.
BS-3D	65.6	16.9
BS-7D	43.1	45.4
BS-28D	40.6	48.5
BS-1Y	39.2	50.3

2) Effect of the Type of New Concrete

Four types were employed for the new concrete of the beams (Sika, SCC, concrete with steel fibers, and HSC). Then their results were compared with the reference beam. According to the data presented in Table VIII, the ultimate load decreases by 16.2%, and 13.3% for the composite beam with new concrete of SCC, and steel fibers, respectively, compared to the reference beam. While the ultimate load increases by 6.5%, and 9% for the composite beam with new concrete of Sika, and HSC, respectively, regarding the reference beam. So, using new concrete with Sika, or HSC is the best choice.

TABLE VIII. ULTIMATE LOAD FOR BEAMS (TYPE OF NEW CONCRETE

Beam ID	Failure load P_u,(kN)	Change Percentage in P_u(%)
BS	78.9	Ref.
BS-SIKA	84	6.5 (increasing)
BS-SCC	66.1	16.2 (decreasing)
BS-SF	68.4	13.3 (decreasing)
BS-HSC	86	9 (increasing)

3) Effect of the Type of Bonding Agent

Two types were deployed for the bonding agent of the composite beams (epoxy and SBR) and their results were compared with the reference beam. According to the data shown in Table IX, the ultimate load decreases by 11%, and 6.7% for composite beam with SBR agent, and epoxy agent, respectively, with respect to the reference beam.

TABLE IX. ULTIMATE LOAD FOR BEAMS (TYPE OF BONDING AGENT

Beam ID	Failure load P_u,(kN)	Decrease Percentage in P_u (%)
BS	78.9	Ref.
BS-SBR	70.3	11
BS-EP	73.6	6.7

4) Effect of the Type of Bonding Method and Surface Roughness

Two types were utilized for this group of the composite beams (old concrete with roughness surface and old concrete with stirrups as shear connectors). Then their results were compared to the reference beam. According to the data presented in Table X, the ultimate load decreases by 1.8% for the composite beam with old concrete of rough surface, concerning the reference beam. While the ultimate load increases by 126% for the composite beam with stirrups as shear connectors with regard to the reference beam. So, using stirrups as shear connectors between the new and old concrete significantly increases the load caring capacity of the beam.

TABLE X. ULTIMATE LOAD FOR BEAMS (TYPE OF AGENT)

Beam ID	Failure load P_u,(kN)	Change Percentage in P_u(%)
BS	78.9	Ref.
BS-SH	178.4	126 (increasing)
BS-RO	77.5	1.8 (decreasing)

V. CONCLUSION

- At service stage the deflection of mid span decreases from 22% to 67% for all beams except for the beam with shear connectors in which deflection increased by 90%. The reason for this is that the ultimate load of this beam is relatively large, and therefore the service load will also be large.
- It is noted that as the age of the old concrete increases, the bond between the old and new concrete decreases, but the strength of the old concrete increases, which leads to the stiffness and load-bearing capacity of the composite beam increasing significantly at the age of one year, with results varying for other ages.
- The ultimate load decreases by 16.2% and 13.3% for the composite beam with new concrete of SCC, and steel fibers, respectively, compared to the reference beam. In contrast, the ultimate load increases by 6.5% and 9% for the composite beam with new concrete of Sika and HSC, respectively, compared to the reference beam. Therefore, employing new concrete with Sika, or HSC is the best choice.
- The ultimate load decreases by 1.8% for the composite beam with old concrete of rough surface compared to the reference beam. While the ultimate load increases by 126% for the composite beam with stirrups as shear connectors, concerning the reference beam. Thus, by using stirrups as

shear connectors between the new and old concrete significantly increases the load caring capacity of the beam.

- All tested beams failed by shear with diagonal tensile fracture except the beam of old concrete with an age of 7 days and the beam with agent SBR. In contrast, the last two beams failed by shear with a diagonal tensile fracture at the upper part (new layer) followed by separation between the two layers

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