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Effects of Externally Bonded GFRP Sheet on Flexural Strengthening under Post-Yielded Reinforced Concrete Beams

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Abstract: ***The application of GFRP sheets as the strengthening material in the damaged reinforced concrete structures have found increasingly wide. Due to yielding of the longitudinal rebars, the load bearing capacity decreases. This study represents the experimental work of the strengthening reinforced concrete beams using externally glass fiber reinforced polymer (GFRP). Six RC beams with 3.3 m length and with dimensions of 150.0 mm x 200.0 mm were tested. The specimens consisted of three normal beams and three strengthened beams. One layer of the GFRP sheet was bonded on the bottom face of the strengthened beam. The results indicated that the flexural capacity of the strengthened beam enhanced up to 17.7% compared to the normal beam. The strengthened beams failed by intermediate flexural crack induced interfacial debonding (IC-debonding). The IC-debonding causes premature failure of the strengthened beam.***

Keyword: **flexural strengthening, IC-debonding, GFRP.**

I. BACKGROUND

Rehabilitation and strengthening of reinforced concrete structural elements is a common task for existing constructions. Strengthening of a structural element is aimed at increasing or restoring the load bearing capacity, due to changes in conditions of use (increased loading) or deterioration and damage of the concrete structure.

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Several materials and methods are available for strengthening reinforced concrete elements, such as adding or applying mortar; spraying concrete or mortar; injecting or filling cracks, voids and interstices; adding reinforcing steel bars; installing bonded rebars; post-tensioning; bonding steel plates or fiber reinforced polymers (FRP) sheets/plates and others[1)].

In particular, externally bonded FRP sheets/plates have found increasingly wide applications in civil engineering due to their high strength-to-weight ratio and high corrosion resistance. A great amount of research, both experimental and theoretical, has been conducted on the behavior of FRP-strengthened RC structures including beams, slabs and columns[2-8)].Main types of FRP composites used in external strengthening and repair of RC structures are: glass fiber reinforced polymers (GFRP), carbon fiber reinforced polymers (CFRP), and aramid\ fiber reinforced polymers (AFRP). CFRP and GFRP are two materials suitable for strengthening RC beams. CFRP has a high strength and a high elastic modulus and is more expensive and its elongation at fracture is relatively small (1–1.5%), while GFRP is cheaper and has a relatively large elongation (3–5.4%). However, the elastic modulus of GFRP is significantly lower than that of CFRP[9)].

In this regard, this study aims to investigate the effects of the externally bonded GFRP sheet on flexural strengthening under post-yielded reinforced concrete beams. During the test, applied load, strain on the concrete compressive

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regions, the tensile steel at mid span, strain at the FRP sheets, and also the deflection at mid span were measured up to failure. The responses of the beams were examined and discussed in terms of deflections, strains, and failure modes, and load capacity.

II. SPECIMENS AND TEST SET-UP

A. Specimens

Two types of concrete beams with three specimens for each type were tested under flexural test. The length of the beams was 3300 mm with the cross section of 150 x 200 mm were tested. They are the normal beam (BN) and the strengthened beam (BG). The normal beams (not strengthened) were loaded until the failure. Meanwhile the strengthened beams were loaded into the two phases. In the first phase, the beams were loaded until the yielding strain of the longitudinal reinforcement of 2000. After that, the beams were strengthened by using one layer GFRP sheets on tension zone of the beam. The U-shape anchorage sheet was also bonded in the transverse direction of the beam.

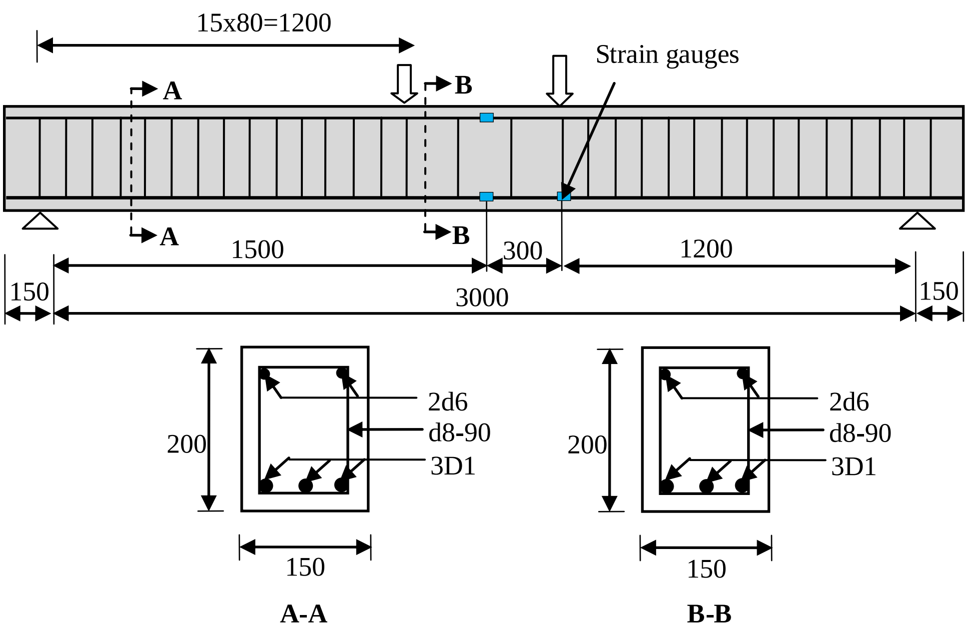

Fig. 1: Details of RC beam (unit in mm)

Finally, in the second phase, the beams were loaded until the failure. The specimen details are presented in **Fig. 1**.

The same percentage of reinforcement was provided in the two types of the specimens. Three numbers of 12 diameter deformed rebars (D12) are provided in the tension zone and two number of 6 mm diameter plain rebars (d6) in the compression zone. In order to avoid shear failure, adequate shear reinforcement provided for the beams.

B. Materials

The concrete used for the experiment was made by ready mix with the designed 28-day cylinder compressive strength of 25 MPa. The concrete compressive strength was measured on 100x200 mm concrete cylinder. The 12 mm deformed rebars and 6 mm plain rebars were tested in tensile and the measured yield strength was 412.5 and 412.5 MPa, respectively. The Young's modulus (E_{fu}) and ultimate tensile stress (f_{fu}) of the GFRP sheet were obtained from the supplier and given in **Table 1**.

Table 1: Mechanical properties of GFRP sheets

Typical dry fiber properties		Composite gross laminate properties		
Properties	Value	Properties	Value	
			Test	Design

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Tensile strength	3.24 GPa	Ultimate tensile strength in primary fiber direction	575 MPa	460 MPa
Tensile modulus	72.4 GPa	Tensile modulus	26.1 GPa	20.9 GPa
Ultimate elongation	4.5%	Elongation at break	2.2%	1.76%
Density	2.55 g/cm^3	Flexural strength	551.6 MPa	468.9 MPa
Thickness	0.36 mm	Thickness	1.3 mm	1.3 mm

C. FRP bonding Procedure

The process of applying FRP sheets to concrete; involved surface preparation, priming, resin under coating, FRP sheet application, and resin over coating. The concrete surface treatment prior to strengthening was very important to guarantee the perfect bonding between two materials. Prior to bonding of the FRP sheets, the beams were ground using a mechanical grinder to obtain a clean sound surface, free of all contaminants and then clean with an acetone solution. After that, a two-part primer was applied to the prepared concrete surface. Next, a two-part epoxy resin was applied to the primed concrete surface, followed by application of the FRP sheet. The FRP sheet was installed over the concrete surface by starting at one end and moving along the length of the FRP sheet until completed. Finally, a resin over coating was applied over the FRP sheet. Concrete beams strengthened with FRP sheets were cured for at least 3 days at room temperature before testing.

D. Instrumentations and loading methods

The beams were subjected to a static four-point bending test as shown in **Fig. 2**. The load was applied by a hydraulic jack setup on a steel contrast frame firmly anchored to the lab floor. The jack was controlled by a hydraulic control unit that imposed the prescribed displacement with the rate of 0.2 mm/sec. A load cell with the capacity of 200 kN was placed between the jack and a distributor beam to measure the applied force precisely. During the loading, all of the measurements were recorded through a data logger. The crack propagations were drawn and marked at each load level during the loading tests.

One transducer was set at the mid-span and the other two were located under the loading points. The arrangements of the transducers are presented in **Fig.2**. Several strain gauges were attached to the tensile reinforcement, concrete and GFRP sheet as shown in **Figs. 1, 3** and **4**, respectively.

Table 2: Mechanical properties of GFRP sheet

Type	Beam	Load (kN)			Displacement (mm)			Failure mode
		Crack	Yield	Ultimate	Crack	Yield	Ultimate	
Normal beam	BN-1	7.1	27.2	29.4	7.1	27.2	89.9	Flexural failure
	BN-2	9.4	27.9	28.9	9.4	27.9	82.5	
	BN-2	7.5	26.8	27.8	7.5	26.8	68.8	
	Average	7.9	27.3	28.7	7.9	27.3	80.4	
Strengthened beam	BG-1	8.2	31.0	35.4	8.2	31.4	84.3	IC debonding
	BG-2	4.1	29.1	33.5	4.1	29.1	78.3	
	BG-3	2.1	30.9	32.5	2.1	30.9	78.9	
	Average	4.8	30.6	33.8	4.8	30.4	54.2	

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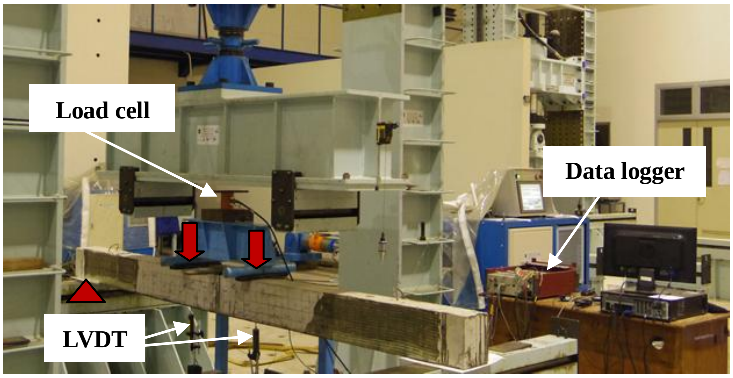

Fig. 2: Loading setup

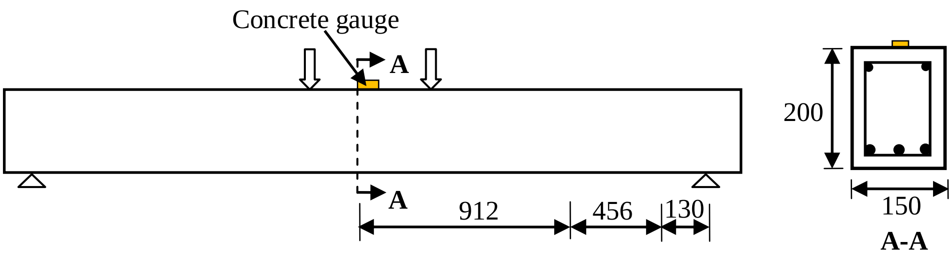

Fig. 3: Arrangement of gauge at concrete

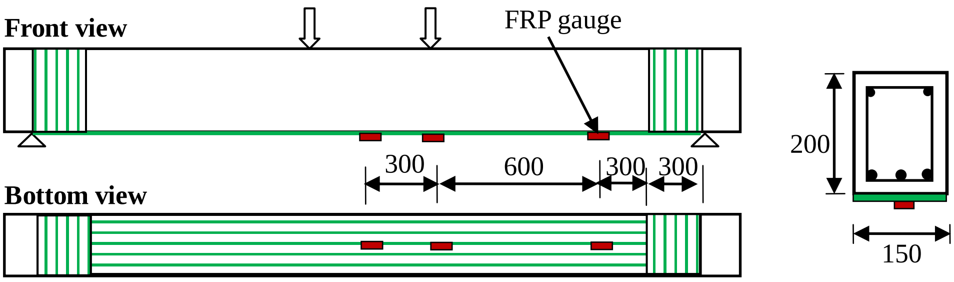

Fig. 4: Arrangement of gauge at GFRP

III. RESULTS AND DISCUSSIONS

A. Load-Displacement Relationship

Table 2 summarizes the experimental results. The load versus deflection at the mid-span of the beam is shown in **Fig. 5**. The solid line in this figure represents the normal

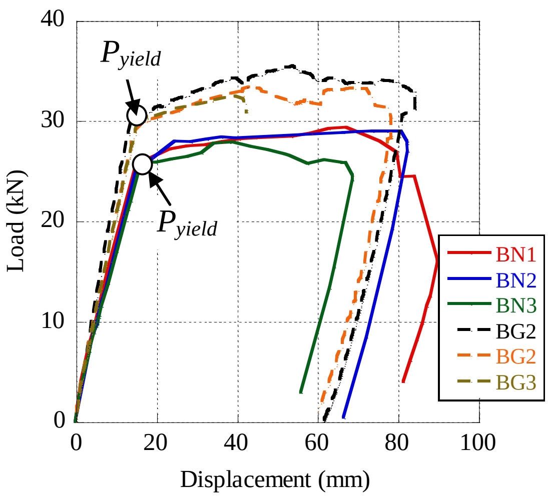

Fig. 5: Load-displacement curve

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beam (BN) while the dashed line represents the strengthened beam (BG). Generally, both the normal beams and strengthened beams show three stage responses up to failure, representing the concrete pre-cracking stage, concrete post cracking tension steel preyield stage, tension steel post yield stage.

In the pre-cracking stage (elastic stage), the same behavior was observed for all tested beams, indicating very similar beams stiffness prior to concrete cracking. In the cracked preyield stage, the stiffness and yield load of the FRP strengthened beams were larger than that of the control beam. As shown in **Table 2**, the yielding load (P_y) for the control beam BN1, BN2 and BN3 was27.2, 27.9 and 26.8kN, respectively with the average of 27.3kN. Meanwhile, the yielding load for the control beam BG1, BG2 and BG3 was 31.0, 29.1 and 30.9kN, respectively with the average of 30.6kN. The results indicated the use of the one layer GFRP sheet in the post-yielded RC beam increased the average yielding load by 11.4% compared to the normal beam.

Similar with the cracked preyield stage, the stiffness and yield load of the FRP strengthened beams were also larger than that of the control beam. By comparing the displacement of the control beam and strengthened beam at the failure load, it was found that the mid-span deflection was increased by using the GFRP sheets. The result indicated that the GFRP sheet increased the beam stiffness after yielding of the tensile steel.

A. Load-Strain Relationship

Figure 6 illustrates the development of the compressive strains in the top fiber of concrete at the mid-span. **Figure 7** shows the relationship between the applied load and the tensile strain in the bonded sheet. The solid line represents the normal beam (BN) while the dashed line represents the strengthened beam (BG). It was observed that the ultimate compressive strains of concrete at the BN1, BN2 and BN3 were1169, 3856 and 2852, respectively. Meanwhile, the ultimate compressive strains of concrete at the BGA1, BGA2 and BGA3 were758, 1760 and 1969, respectively. The outcomes implied that the BN failed when the concrete reached the ultimate strain of concrete (assumed to be equal to 3000). On the other hand, the BG failed before reached the ultimate strain of concrete.

From **Fig. 7**, it was seen that the measured the tensile strain in the bonded sheet at the peak load was 5471□ □, 6397□ □, and 7454□ □□for BGA1, BGA2 and BGA3, respectively. These values were smaller than the ultimate strain ($□_{fu}$) of GFRP sheet (equal to 20000□ □ □). Thus, it was concluded that the strengthened beam failed due to the debonding of the bonded sheet.

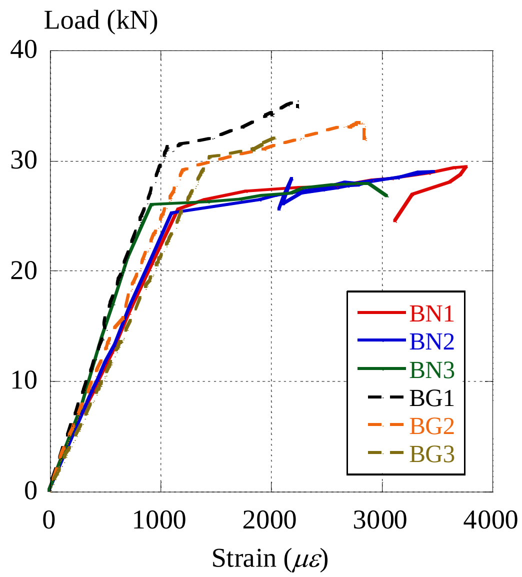

Fig. 6: Load-strain of concrete

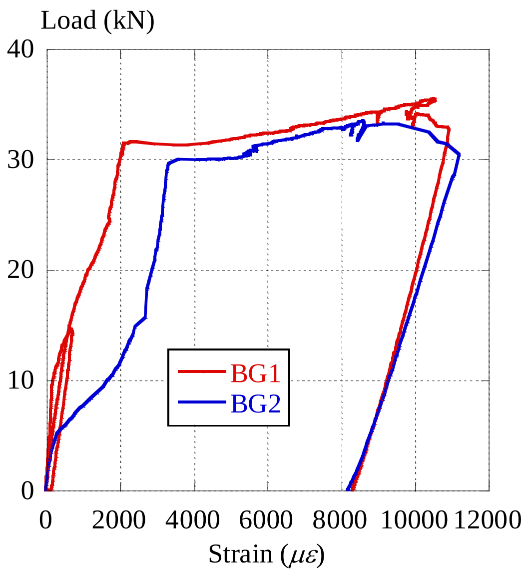

Fig. 7: Load-strain of FRP

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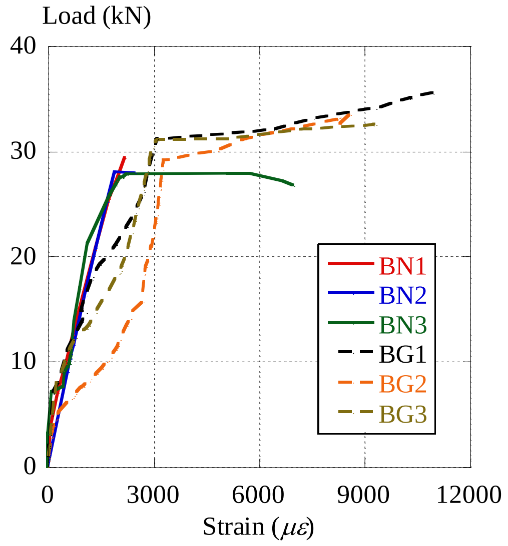

Fig. 8: Load-strain of tensile rebars

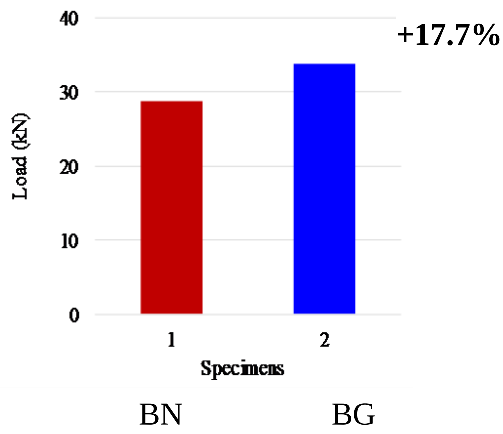

Fig. 9: Average enhancement of failure load

The strain development in tensile rebars during the loading test is shown in **Fig. 8**. Since the bonded sheet contributed in carrying the tensile strain in the strengthened beams, the increment of tensile strains of longitudinal rebars was decreased at the same load levels.

B. Enhancement of Failure load

The normal beams were loading until the failure. Meanwhile, the strengthened beams were loaded until the yielding strain of the longitudinal rebars. After that, the strengthening method was applied and re-loaded until the failure. **Figure 9** summarizes the average ultimate failure load enhancement ratio, which is the ratio of the ultimate load of an externally strengthened beam to that of the control beam. As indicated in **Fig. 8**, the average failure load of control beam was 28.7 kN while the average failure load of strengthened beam was 33.8 kN.The results indicated that the use of one layer of GFRP sheet in the strengthened beam caused to increase the average ultimate capacity by 17.7% compared to the control beam.

The increasing of the maximum load on the strengthened beam was due to the contribution of the GFRP sheet. When the applied load was increased and when the longitudinal rebars yield, the beam was able to resist the applied load as long as the GFRP sheet still bonded on the concrete surface[2)].

Failure mode

Two different failure modes were observed and are described as follow. The different typical of failure are shown in **Fig. 10**.

The control beam failed in the RC conventional flexural manner (**Fig. 10(a)**). The tensile steel yielded prior to concrete crushing at mid-span section. The wide flexural cracks were occurred at mid-span. This crack was extended to the compressive regions.

Figure 10(b) shows typical of failure for strengthened beams. The beam failed by intermediate flexural crack induced interfacial debonding (IC debonding). The IC-debonding caused premature failure of the strengthened beam and it can significantly limit the capacity enhancement and prevent the full ultimate flexural capacity of the strengthening beam. At the failure, the U-shape straps did not rupture. Moreover, **Fig. 11** also indicated that by strengthening the beam using GFRP sheet, the beam flexural capacity is increased and therefore more number of flexural cracks are occurred and developed towards the neutral axis before beam failure.

The mechanism of IC debonding may be summarized as follows, when a major flexural crack is formed in the concrete, the tensile stresses released by the cracked concrete are transferred to the FRP sheet. As a result, high local interfacial stresses between the FRP sheet and the

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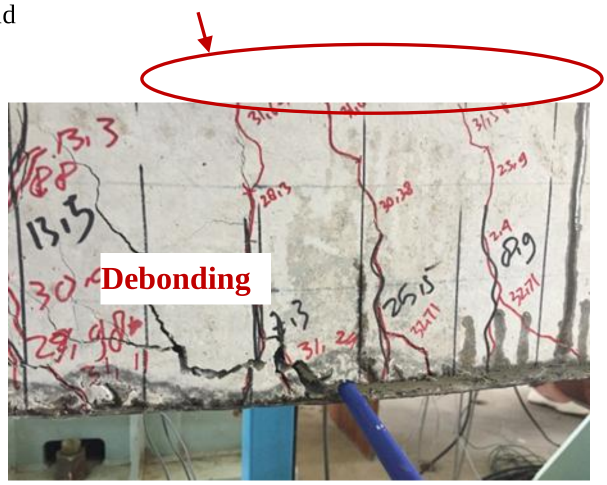
concrete are induced near the crack. As the applied loading increases further, the tensile stresses in the sheet and hence the interfacial stresses between the FRP sheet and the concrete near the crack also increase. When these stresses reach critical values, debonding initiates at the crack and then propagate towards one of the sheet ends[9].

a. Normal beam (BN)



b. Strengthened beam (BGA)

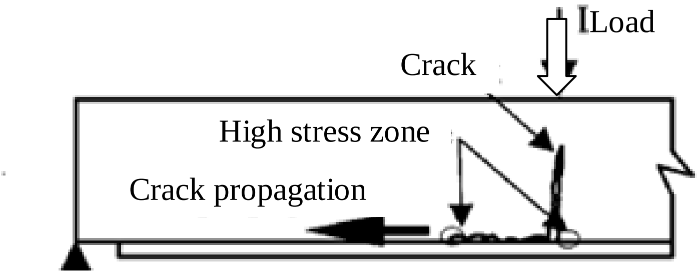


Fig. 11: Mechanism of IC debonding

IV. CONCLUSION

The effects of the externally bonded GFRP sheet on flexural strengthening of post-yielded reinforced concrete beams were investigated in this study. The results are summarized as follows:

a. Externally bonded GFRP sheet method effective to enhance the flexural capacity as well as the stiffness of post-yielded reinforced concrete beams. The flexural capacity was enhanced up to 17.7% than the normal beam.

b. The strengthened beams failed by intermediate flexural crack induced interfacial debonding (IC debonding). The IC-debonding causes premature failure of the strengthened beam and it can significantly limit the capacity enhancement and prevent the full ultimate flexural capacity of the strengthening beam

V. ACKNOWLEDGEMENT

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