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Tests on Reinforced Concrete Slabs with Pre-stressing and with Transverse Reinforcement under Impact Loading

Nebojsa Orbovic[a], Medhat Elgohary[b], Namho Lee[b], and Andrei Blahoianu[a]

[a]*DAA/EDAD, CNSC-CCSN, Ottawa, Ontario, Canada , e-mail: nebojsa.orbovicr@cnsc-ccsn.gc.ca*
[b]*AECL-EACL, Mississauga, Ontario, Canada*

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1 ABSTRACT

Current empirical formulae for design of concrete elements under impact loading are based on tests carried out on reinforced concrete elements with longitudinal reinforcement and they are applicable only to such elements. The influence of pre-stressing or transverse reinforcement is not taken into account. The aim of this test campaign carried out at VTT testing facility in Espoo, Finland, was to assess the influence of longitudinal pre-stressing and transverse reinforcement, separately and combined, on punching resistance of concrete elements under impact loading. Six tests presented in this paper were carried out on low aspect ratio concrete slabs under medium velocity hard missile impact. The variables were: the level of pre-stressing and the transverse reinforcement in form of T-headed bars. The results are presented in terms of scabbed concrete area and permanent deflection for each tested slab. It was observed that the level of damage of pre-stressed concrete elements without transverse reinforcement, in terms of scabbed area, was higher than reinforced concrete elements although the permanent deflections are lower. On the other hand, the transverse reinforcement reduces scabbed area as well as the level of permanent defections.

2 INTRODUCTION

Current empirical formulae for design of concrete elements under impact loading are based on tests carried out on reinforced concrete elements with longitudinal reinforcement and they are applicable only to such elements Buzaud et al. (2007), Sliter (1980). The design acceptance criteria according to these formulae are based on the damage of a concrete element. More precisely, they are based on the description of the visual damage of the rear side of the concrete element and formulated as scabbing of the concrete surface or missile perforation through the element. There is no quantification of the damage in terms of width and depth of the scabbed area or in terms of deflection of the element. The failure mechanism and the aspect ratio of testing specimens, as an important parameter that can influence the failure mechanism, are rarely mentioned. Taking into account the description of the damage (scabbing or perforation), the failure mode of the element is apparently a punching failure mode.

The influence of pre-stressing or transverse reinforcement is not taken into account in current empirical formulae. However, the code provisions ACI 318-05 (2005) and CSA-A23.3 (2004) for punching resistance of concrete elements under conventional loadings, take into account beneficial effect of these parameters. The nature of conventional static or dynamic loading is different from impact loading and therefore the influence of these parameters on punching resistance, for this type of loading, can be different.

Six concrete slabs with the same geometry were tested under hard missile impact. The goal of the campaign is to compare the level of damage of a reference reinforced concrete wall to the level of damage of the walls with pre-stressing and transverse reinforcement, separately and combined, and therefore to asses the influence of these parameters on punching resistance of concrete slabs under impact loading. To perform this comparison of some quantifiable results, in terms of scabbed and cracked concrete area as well as permanent slab deflections and punching cone angles, are provided to describe the level of damage.

3 DESIGN OF TEST SPECIMENS

The test specimens were designed using existing empirical formulae for reinforced concrete slabs under impact loading. Three formulae were used: CEA-EDF, Chang's and CRIEPI formula for perforation and Chang's, CRIEPI and BECHTEL formulae for scabbing. The aspect ratio of the concrete slab and its thickness as well as missile the mass, velocity and the diameter of the missile were chosen, based on previous tests, Buzaud et al. (2007), Sliter (1980), Tarallo et al (2007), to achieve punching failure mode. CEA-EDF, CRIEPI and Chang's perforation formulae are presented respectively:

$$V_{CEA-EDF} = \left(\frac{h * f_c^{'\frac{3}{8}} * D^{0.5}}{0.00057 * M^{0.5}} \right)^{1/0.75} \quad \text{[m/s]} \tag{1}$$

$$V_{CRIEPI} = \left(\frac{h * f_c^{'0.5} * D^{0.5}}{0.0008 * M^{0.5}} \right)^{1/0.75} \quad \text{[m/s]} \tag{2}$$

$$V_{Chang} = \left(\frac{h * f_c^{'0.5} * D^{0.5}}{0.0009 * M^{0.5}} \right)^{1/0.75} \quad \text{[m/s]} \tag{3}$$

BECHTEL, CRIEPI and Chang's scabbing formulae are presented respectively:

$$V_{BECHTEL} = \left(\frac{h * f_c^{'0.5} * D^{0.2}}{0.015 * M^{0.4}} \right)^{1/0.5} \quad \text{[m/s]} \tag{4}$$

$$V_{CRIEPI} = \left(\frac{h * f_c^{'0.4} * D^{0.2}}{0.0047 * M^{0.4}} \right)^{1/0.67} \quad \text{[m/s]} \tag{5}$$

$$V_{Chang} = \left(\frac{h * f_c^{'0.4} * D^{0.2}}{0.005 * M^{0.4}} \right)^{1/0.67} \quad \text{[m/s]} \tag{6}$$

Where h is he thickness of the slab, f'_c is the compressive concrete strength, D is missile diameter and M is the mass of the missile.

The geometry of all specimens is the same: 0.25 m thick and 2.1 m square slab. The slab is simply supported and the supported length is 2.00 m in both directions (Figure1). The aspect ratio (h/L, where h is the thickness of the specimen and L is its supported length) of the slab is 1/8. The diameter of the missile is constant as well and equal to 0.168 m. The concrete compressive strength of specimens, casted at different times from different batches can vary. The mass of the missile in each test can vary slightly as well.

Six specimens were tested: A – the reference specimen with longitudinal reinforcement only, B – the specimen with pre –stressing level in both longitudinal directions of 5 MPA, C- pre-stressing level in both longitudinal directions of 10 MPa, D specimen with longitudinal reinforcement and transverse reinforcement in form of T-headed bars, E – specimen with longitudinal reinforcement, T-headed bars and pre-stressing level of 5 MPa in both directions and F – specimen with longitudinal reinforcement, T-headed bars and pre-stressing level of 10 MPa in both directions.

The longitudinal reinforcement ratio was kept constant in all six specimens: 10 mm deformed bars with yield strength of 500 MPa are spaced at 90 mm at each face and in each direction. The longitudinal reinforcement ratio is 0.35% per face and per direction.

The pre-stressing was introduced using 26.5 mm diameter pre-stressing bars (A_{ps}= 548 mm^2) spaced at 180 mm. The bars are placed in plastic sleeves and they are not in contact with the concrete. The ultimate stress of the bars is f_{pu} = 1030 MPa. The bars are anchored with external anchors (Figure 2).

The transverse reinforcement utilized in this campaign is in form of friction-welded T-headed 12 mm diameter bars (f_y = 500 MPa) spaced at 90 mm in each direction. One T-headed bar was placed at each intersection of longitudinal reinforcement. The diameter of T-headed bars anchor plates (f_y = 450 MPa) is 35 mm and the thickness is 8 mm.

The slabs were impacted by a hard steel missile with concrete infill (Figure 1). Approximate mass of the missile is 47 kg.

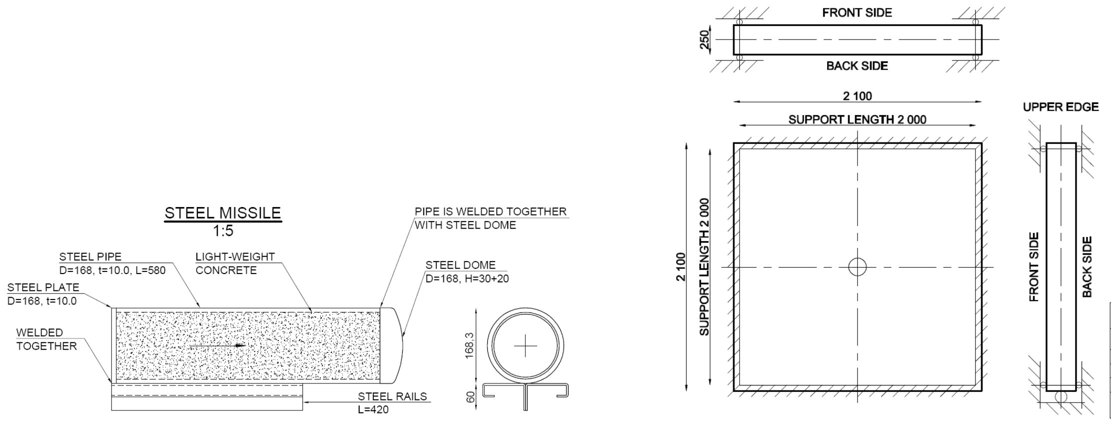


Figure 1. Missile geometry (on the left) and slab geometry and boundary conditions (on the right)

Each specimen was poured at a different time and measured concrete strengths are presented in **Table 1**.

Table 1. Concrete Strength of Specimens [MPa].

Specimen	A	B	C	D	E	F
Comp str. cube	58	62.5	58.5	54	55.0	54.0
Comp. str. cylinder	48.3	52.1	48.7	45.0	45.8	45.0
Tensile str.	4.0	4.1	3.9	3.0	3.0	3.3

Perforation and scabbing velocities are calculated using the formulae (1) to (6) and the results are presented in Table 2. The missile velocity is chosen to be significantly higher than scabbing velocities but below the perforation velocities given by the formulae. The chosen velocity was 100 m/s. The missile velocity was chosen to achieve significant damage of the reference slab but without perforation.

Table 2. Perforation and scabbing velocities predicted by empirical formulae [m/s].

Specimen	A	B	C	D	E	F
PERFORATION VELOCITIES						
Vcea-edf	116.6	121.0	117.3	112.3	113.6	112.3
Vcriepi	141.7	148.8	142.6	134.7	136.7	134.7
VChang	121.1	127.2	121.9	115.2	116.9	115.2
SCABBING VELOCITIES						
Vbechtel	47.8	51.6	48.4	44.5	45.4	44.5
Vcriepi	56.8	59.4	57.2	54.4	55.1	54.4
VChang	51.8	54.2	52.2	49.6	50.2	49.6

It should be noted that the ratio of longitudinal reinforcement of the slab is not taken into account in the current formulae. Only CEA-EDF formula requires a minimum reinforcement amount of 150 kg/m3. The reinforcement ratio of the reference Specimen A gives the amount of longitudinal reinforcement of 110 kg/m3. Lower value for longitudinal reinforcement is chosen to facilitate placing of pre-stressing bars and transverse reinforcement in Specimens B to F. It should be point out the meaning of "perforation velocity" in empirical formulae: the "perforation velocity" is a minimum velocity for which the missile goes through the slab with residual velocity equal to zero, Buzaud et al. (2007).

Table 4. Measured velocities, missile mass, momentums and kinetic energies.

Specimen	A	B	C	D	E	F

Missile Vel. [m/s]	103	101.9	99.4	99.7	98.4	98.4
Missile mass [kg]	47	47.1	46.9	47.2	47.0	47.2
Momentum [kgm/s]	4841	4799	4662	4706	4625	4644
Kinetic energy [kgm^2/s^2]	249312	244534	231694	234586	227540	228508

4 EXPERIMENTAL SETUP

The tests were carried out in VTT testing facility in Espoo, Finland. The facility is presented in Lastunen and al (2007). For this test campaign a new two-way frame (Figure 2) and a new hard missile (Figure 1) were developed.

The pre-stressing was introduced using post-tensioning system with bars in PVC sleeves, as shown in Figure 2**.** The bars were placed to introduce compression and minimizing the moment due to their eccentricity as shown in Figure 2.

Figure 2. Steel frame with a specimen after the test (on the left) and pre-stressed specimen (the same setup for the specimens B and C) in the formwork before concrete pouring (on the right).

The tests are designed to develop punching failure mode in the slabs with schematic damage presented in Figure 3

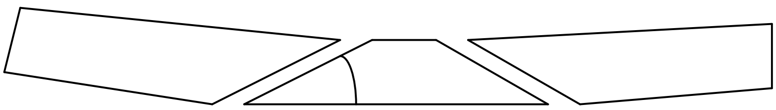


Figure 3. Punching cone developed under the impact and defined with the angle .

5 TEST RESULTS

5.1 Specimen A – Reference specimen with longitudinal reinforcement only

The damages of the reference specimen on both sides are presented schematically in Figure 4. Scabbed area is painted in darker gray colour. In lighter gray colour is presented which is not scabbed but cracked under concrete surface. The crack can be observed on the cross sections of the slabs. The results, in terms of the depth of the hole on the front face, scabbed and cracked area as well as the maximum permanent deflection, are presented in Table 5**.** The value of the maximum permanent deflection is measured at the level of the apparent reinforcement on the rear side. The values given in Table 5 include 20 mm of scabbed concrete cover. The structural behaviour of the wall is punching behaviour. The missile left 120 mm deep whole with one broken vertical rebar and rebounded from the concrete slab after the impact. Scabbed area, at the rear side, is larger in vertical than in horizontal direction although cracked area has the same width in both directions. Larger scabbed area in vertical direction can be attributed to the pull-out of the vertical reinforcement which is in the first layer. The cracked area, at the rear side, is approximately 1.4 m wide in both directions. It gives the angle of the punching cone (as defined in Figure 3) of = 23 degrees.

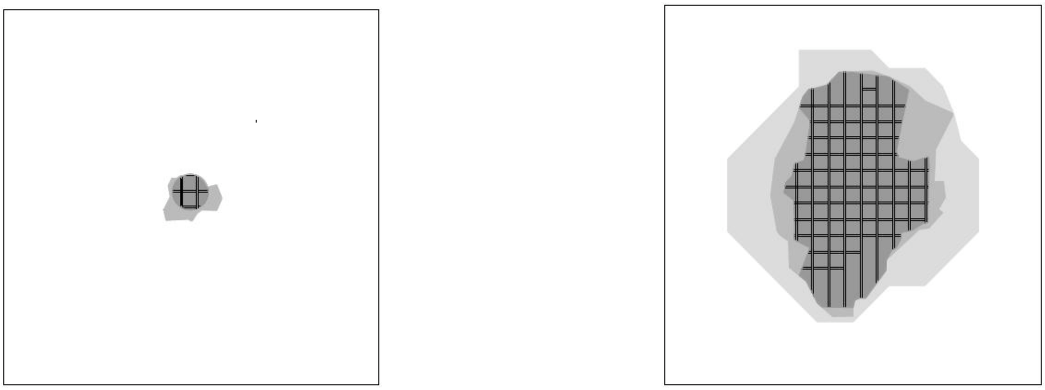


Figure 4. Front and Rear face of the Specimen A after the impact

5.2 Specimen B – Pre-stressed specimen 5 MPa

The schematic damage of the Specimen B is presented in Figure 5 and main results in Table 5. The Missile was anchored in the slab after the test. After removing the missile, a 130 mm deep whole was measured with disaggregated concrete at the bottom. A thru-section whole appeared after the removal of the disaggregated concrete. The scabbed and the cracked areas, at the rear side, are larger in horizontal than in vertical direction which can be due to different boundary conditions in the two directions. The cracked area is approximately 1.4 m wide in vertical direction and 1.7 m in horizontal direction. It gives the angle of the punching cone (as defined in Figure 3) of approximately = 23 degrees in vertical and = 18 degrees in horizontal direction.

Figure 5. Front and Rear face of the Specimen B after the impact

5.3 Specimen C – Pre-stressed 10 MPa

The schematic damage of the Specimen C is presented in Figure 6 and main results are presented in Table 5. The missile, in this test, left a 110 mm deep whole and rebounded after the impact. Although the scabbed are is larger in horizontal direction, the width of the cracked area is the same in both directions. The width of the crack area is almost equal to the supported length and equal to 1.7 m approximately. The angle of the punching cone is = 18 degrees, approximately.

Figure 6. Front and Rear face of the Specimen C after the impact

5.4 Specimen D – Reinforced with T-headed bars as transverse reinforcement

The schematic damage of the Specimen D is presented in Figure 7 and main results in Table 5. The specimen contains transverse reinforcement in form of T-headed bars. The missile left a shallow, 38 mm deep whole, and rebounded after the impact. The scabbed and cracked areas at the rear side coincide. This area is significantly reduced comparing to cracked are in three previous tests. The area is 0.7 m wide in both directions. The angle of the punching cone is approximately = 44 degrees.

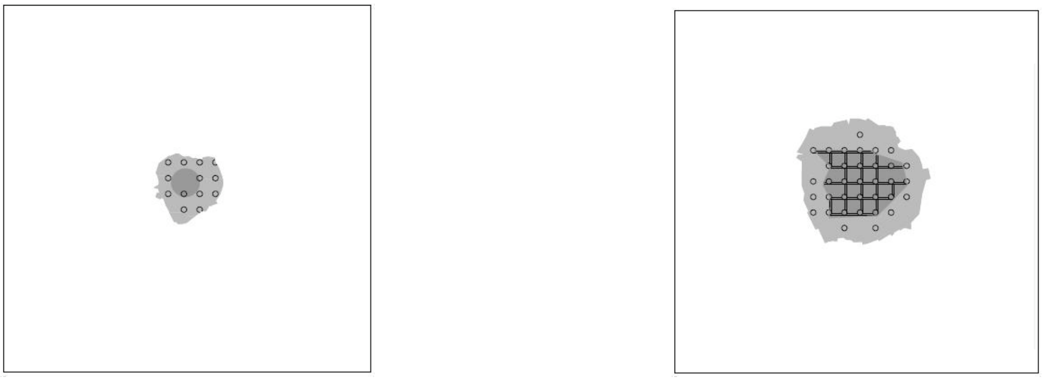
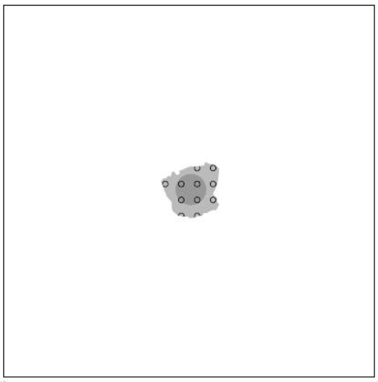


Figure 7. Front and Rear face of the Specimen D after the impact

5.5 Specimen E – 5 MPa longitudinal pre-stressing and T-headed bars as transverse reinforcement



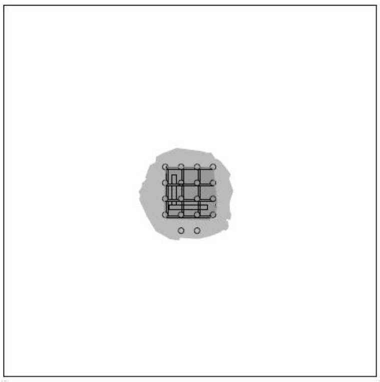
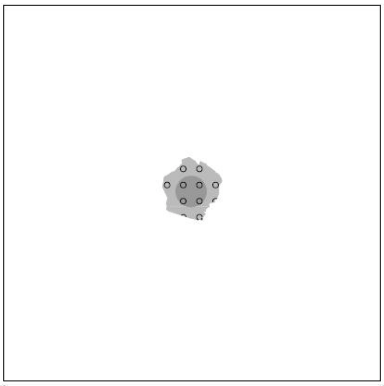


Figure 8. Front and Rear face of the Specimen E after the impact

The schematic damage of the Specimen E is presented in Figure 8 and main results in Table 5. This specimen presents combined pre-stressing with transverse reinforcement. The missile left a 47 mm deep whole and rebounded after the impact. The scabbed and cracked areas coincide, as in the previous tests. The damaged area in this case is even smaller than in Specimens A to D and the failure mode is modified. The width of the damaged area at the rear side, in both directions, is approximately 0.5 m. However, the most damaged part is almost reduced to the impact surface of the missile. The punching cone is therefore reduced to a punching cylinder.

5.6 Specimen F – 10 MPa longitudinal pre-stressing and T-headed bars as transverse reinforcement

The results presented in Figure 9 are very similar to the results of the Specimen E with the level of pre-stress of 5 MPa. The punching cone is reduced to a punching cylinder. However, the deformation is higher at both surfaces of the specimen. The T-heeded bars in direct contact with the missile were pushed-in deeper than in Specimen E.



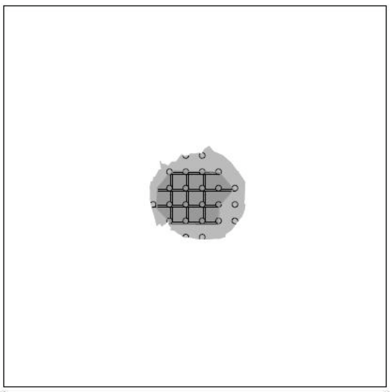


Figure 9. Front and Rear face of the Specimen F after the impact

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5.7 Main Test Results and Discussion

The main test results are presented in Table 5**.**

Table 5. Main Test Results

Specimen	A	B	C	D	E	F
Impact depth [mm]	120	130	110	38	47	74
Scabbing area [mm^2]	0.93	0.99	0.67	0.41	0.18	0.18
Cracked area[mm^2]	1.52	2.02	2.66	0.41	0.18	0.18
Crack are/ scab. area	1.63	2.04	3.97	1	1	1
Residual maximum deflection [mm]	105	97	84	40	45	55

A testing campaign using medium velocity hard missile and comprising six two-way slabs was carried out to assess the influence of pre-stressing and transverse reinforcement, in form of T-headed bars, on punching resistance under impact loading. The tests were performed on limited number io specimens and therefore the authors want to highlight that the results are specific to the range of parameters used in these tests and taking into account uncertainties that are yet to be assessed. Code provisions ACI 318-05 (2005) and CSA-A23.3-04 (2004) for conventional loading take into account beneficial effects of both parameters. Similar effects were expected under impact loading.

The results presented in Table 5 show that the pre-stressing (Specimens B and C comparing to the Specimen A) increases the stiffness of the impacted slab: the maximum deflections of the slab decrease with increasing level of pre-stressing. On the other hand, the cracked concrete area increases showing that the angel of the punching cone, created in the slab, decreases. Regarding the size of the whole on the front face, created by the missile impact as well as the scabbed area at the rear side, the results are more difficult to interpret. Despite the highest value of concrete strength (the compressive as well as the tensile strength) the deepest whole on the front side as well as the largest scabbed area were created in the test with the Specimen B. The kinetic energy of the missile was slightly higher in the test with the Specimen B (6%) but it can not explain the difference in the results. Transverse reinforcement (Specimen D comparing to the Specimen A) reduces significantly scabbed area (2.3 times), cracked area (3.7 times) as well as residual deflections (2.6 times). The uncertainties have to be assessed using repeated tests.

Transverse reinforcement combined with pre-stressing reduces even more the damaged area comparing to the specimens without pre-stressing (2 times). However, in this case the failure mode is changed. The damage is concentrated to the area comparable to the missile contact surface. The punching cone is reduced to a punching cylinder. The maximum damage occurs at the level of T-headed bars in direct contact with the missile contact surface. It can be observed that the T-headed bars were pushed-in deeper when the level of pre-stressing was higher. Neither the head nor the weld between the head and the bar, of T-headed bar, were damaged. The maximum deformation is still below the deformation without T-headed bars but higher than the maximum deformation without pre-stressing. Once again, it should be pointed out that the failure mode is not the same in the case of Specimens A to D and the Specimens E and F

6 CONCLUSION

A testing campaign, on low aspect ratio concrete slabs (h/L = 1/8), was conducted keeping the same velocity of the missile and modifying slab characteristics (pre-stressing and transverse reinforcement). The goal was to compare the level of damage, taking into account the level of pre-stressing and the presence of transverse reinforcement. To facilitate this comparison, the chosen velocity is below the minimum perforation velocity given by three empirical formulae. The comparison gives clear trends regarding the effect of pre-stressing and transverse reinforcement in form of T-headed bars.

Pre-stressing increases the stiffness of the slab. The increase of the stiffness decreases the slab's deflections. Pre–stressing decreases the angle of the punching cone as well. Decreasing the angle of the punching cone increases the damaged area of the slab.

Transverse reinforcement (T-headed bars) decreases the deflections and increase the angle of the punching cone. Increasing the angle of the punching cone decreases the damaged area of the impacted elements.

Transverse reinforcement (T-headed bars) combined with pre-stressing decrease significantly the damaged area. The failure mode is modified in this case and the damage is concentrated in the area of the missile impact surface.

The conclusions above are based on the missile velocity below the perforation velocity of reference reinforced concrete specimen (100 m/s). To asses the influence of pre-stressing and transverse reinforcement on ultimate capacity (perforation) further tests are needed with higher velocity level.

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