Building Contents Sliding during Earthquakes

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ABSTRACT: Sliding of building contents in simple elastic structures is quantified under both impulse and recorded ground motions. A normalised friction coefficient, equal to the friction coefficient divided by the spectral acceleration of the motion in terms of gravity, derived from the closed-form solution to the first sliding excursion of the impulse motion, is used to characterise sliding demands. The closed-form solutions to impulse motions are relatively independent of the structural fundamental period, and the magnitude of the shaking. The proposed numerical expression (sliding spectra) represented the total peak response of structures well when the normalised friction coefficient is greater than 0.35. However, for structures with lower normalized friction coefficients, sliding excursions subsequent to the first excursion also contribute to the peak sliding from numerical integration. Impulse record sliding spectra can generally represent the median sliding spectra from earthquake motions. The usefulness of the proposed sliding spectra is illustrated via a design example.

1 INTRODUCTION

The recent Canterbury earthquakes resulted in significant contents damage in buildings which had little structural damage. Some such cases includes: (i) microwaves moving several metres across rooms, (ii) heating, ventilation, and air-conditioning (HVAC) units sitting on top of roofs of multi-storey buildings being displaced, (iii) books and computers sliding off shelves and tables, and (iv) contents sliding on floors. As sliding or movement of objects can result in economic loss and injury, it is important that it be quantified so that it may be included in economic loss considerations, or so that mitigation steps may be undertaken.

Since the 1906 San Francisco earthquake, a number of studies have been carried out on sliding behaviour, including the theoretical and/or experimental investigations into the blocks sliding response to earthquake motions (e.g. Aslam et al. 1975, Younis and Tadjbakhsh 1984, Shao and Tung 1999, Choi and Tung 2002, Garcia and Soong 2003, Hutchinson and Chaudhuri 2006, English et al. 2012), the derivation of formulation and criteria for rigid bodies to base excitation (e.g. Shenton and Jones 1991, Shenton 1996, Taniguchi 2002), and in field of soil mechanics where sliding blocks are analysed (e.g. Newmark 1965, Gazetas et al. 2009). Also, there are many observations of contents sliding and falling off shelves during recent significant earthquakes, namely the 1976 San Fernando, the 1989 Loma Prieta, the 1994 Northridge, and the recent Canterbury earthquakes (e.g. Jennings et al. 1971, Ding et al. 1990, Hall 1995, Dhakal 2010). Loss estimation studies show that building contents damage, together with non-structural damage contents, may be four times greater than the structural damage in construction cost (Taghavi and Miranda 2003). This high rate of contents to structural damage is generally larger in moderate levels of ground shaking such as the 2010 Darfield earthquake where there was little structural damage to well-designed structures, but more significant damage to non-structural components and contents (Dhakal 2010).

English et al. (2012) carried out a study to understand the mechanism of building contents sliding and to evaluate what properties of the structure and ground motions influence the degree of sliding. The analytical model of the contents sitting on a single-structure was modelled as a two degree-of-freedom system where the mass of the contents was much less than that of the structure, and the two were connected with an elastic-plastic spring. The structure and contents were undamped. Some findings from the response of the structure after impulse analysis include:

- i) The sliding mechanism of contents on a structure was similar to that of blocks sliding on the ground presented by Aslam et al. (1975).
- ii) As the structural period increased or yield strength decreased, the sliding displacement decreased as a result of the lower floor accelerations.
- iii) Yielding structures tend to cause lower sliding displacements than elastic structures, Non-linear elastic hysteresis loops tend to have greater sliding displacements than bilinear loops.

For oscillators subject to a suite of records, English et al. (2012) found that the peak sliding was greater for oscillators with linear elastic hysteresis loops, than for yielding oscillators with slackness, flag-shaped, bilinear, or Ramberg-Osgood hysteretic characteristics. Also, the demand decreased with lower structural yield strength.

Most seismic codes, including Eurocode 8 (CEN 2004), IBC 2012 (ICC 2011), and NZS 1170.5 (SNZ 2004), provide simple methods to estimate the forces required to anchor contents against moving. These methods generally consider parameters such as the mass of contents, the acceleration for the appropriate floor level, the structural period, the soil condition, and the importance factor of the building. It is generally applied only to specific contents regarded as being important. For heavy contents, which may affect the structural response, interaction must be considered. In addition to the minimum design force requirement, a relative displacement between two attached points of a component is also given in the above-mentioned codes. The anticipated relative displacement is determined using design earthquake level, structural, non-structural, and component properties.

It may be seen from the above discussion that a number of studies have been conducted to understand the behaviour of contents during earthquake motions and that methods are available to determine design forces to limit content movement in a building during earthquake excitation. However there is a need to understand the parameters affecting the magnitude of contents sliding within buildings which can result in physical and human losses.

This paper aims to address this need. This is done by seeking answers to the following questions:

- i) Can a simple analytical expression be developed for the sliding of contents in an elastically responding structure subject to impulse ground motions?
- ii) Can the expression derived in i) be compared to observe suitability for structures subjected to a suite of ground motion records?

2 CONTENTS SLIDING MECHANISM

2.1 Building Contents Sliding Model

The simple two-degree-of-freedom structure-contents sliding system of English et al. (2012) was used to simulate the building and contents behaviour as shown in Figure 1. In these studies structural damping was included. The hysteresis behaviour of structure is described via spring component S, while the behaviour between contents and floors follows Coulomb's law of friction. The frictional behaviour of the contents-floor interaction was modelled using a bilinear hysteresis rule with a high initial stiffness. The sliding force, $F_{resisting}$, was set to μmg, where μ is the coefficient of friction (*COF*) that is assumed to be constant and the same for dynamic and static loading, m is the contents mass, and g is the acceleration of gravity. Sliding will initiate only when the total structural floor acceleration, $a_{structure}$, is greater than μg. A ratio between m and the structural mass, M, of 1:1000 is assumed (Toro et al. 1989) to mitigate the likely interaction between contents and structure. The inherent structural damping effect should be included and is expressed in terms of percentage of critical damping ξ, as shown in Figure 1. In order to quantify the behaviour of contents sliding, the contents movement, Δ, which is defined as the relative displacement between the structure floor and the contents is utilized in the following analyses. The computer software RUAUMOKO-2D (Carr 2008) is used to perform the numerical analyses.

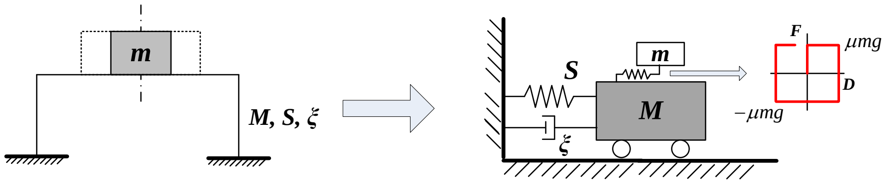


Figure 1. Idealisation and model of structure-contents sliding system

2.2 Sliding Mechanism due to Impulse Excitation

In order to understand the sliding mechanism, a linear elastic structure subject to impulse record is first conducted. The impulse record has been shown to be a powerful tool to understand seismic response (e.g. Newmark 1965, MacRae et al. 2008). The impulse acceleration during the first timestep of the record is followed by zero further acceleration for all other timesteps resulting in free vibration response. Figure 2 shows the total acceleration, the floor and contents velocities relative to the ground, and the contents sliding movement history. As can be seen, a full sliding behaviour can be divided into the following stages:

- O - A: The structure and contents respond together.
- A - B: Sliding has been initiated at A as $a_{structure}>\mu g$, and continues to the peak velocity of the structure.
- B - C: Continued sliding, past the peak velocity position, until the velocity in the contents becomes the same as that in the structure. The total acceleration of the structure at C is greater than μg required to initiate sliding, but in the negative sign. Because of this, sliding immediately initiates in the opposite direction to that previously.
- After C: Continued sliding occurs, but in the opposite direction to the previous sliding and it reduces the total residual sliding displacement between the structure and contents.

The magnitude of contents sliding movement is equal to the integral of the relative velocity with time, or the area between the relative velocity curves of the structure and contents (Newmark 1965, Aslam et al. 1975, English et al. 2012). This is shown in shaded in Figure 2 for the first sliding excursion.

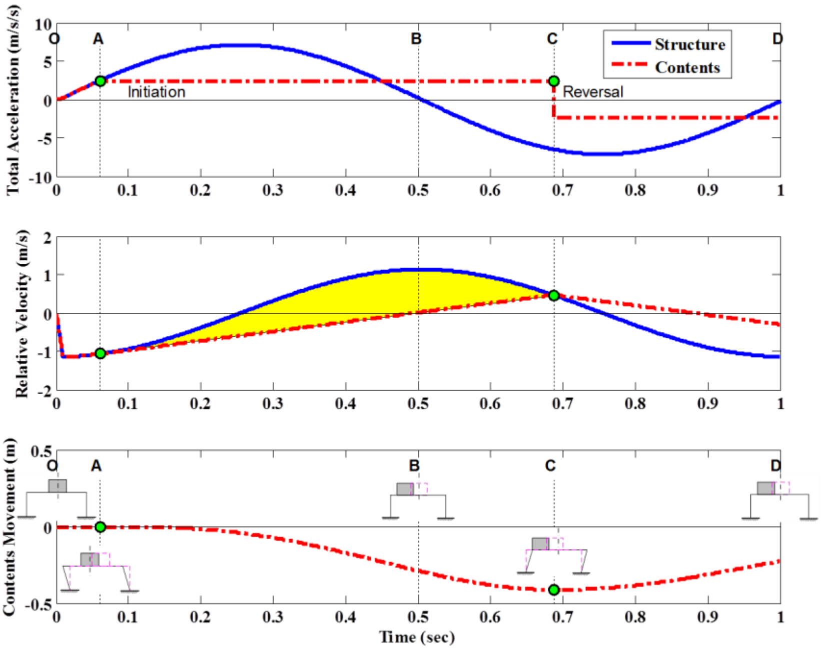
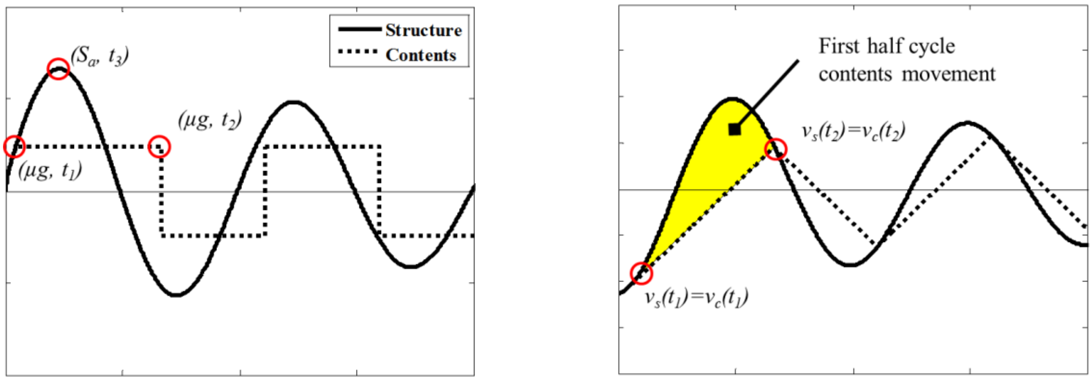


Figure 2. Contents sliding in an elastic structure due to initial impulse loading

3 CONTENTS SLIDING QUANTIFICATION DUE TO IMPULSE EXCITATION

3.1 Contents Movement of an Elastic Structure

A linear structure with viscous damping subjected to impulse loading has a decrease in response amplitude with time as shown in Figure 3. The structural acceleration, a_s (m/s^2), and velocity, v_s (m/s), histories as shown in Figure 3, can be represented using Equations 1 and 2 respectively where S_a is the peak structural acceleration (m/s^2), w is the structural frequency (rad/s), and ξ is the structural damping ratio.



(a) Acceleration history (b) Velocity history

Figure 3. Response of structure with damping and contents

$$a_s(t) = S_a \cdot sin(wt) \cdot e^{-\xi wt} \tag{1}$$

$$v_s(t) = -\frac{S_a}{w}[cos(wt) + \xi \cdot \sin(wt)] \cdot \frac{e^{-\xi wt}}{\xi^2 + 1} \tag{2}$$

For typical structures, the inherent damping ratio, ξ, is generally considered to be less than or equal to 5%. Because of this the value of ξ^2 is small so Equation 2 can be simplified to:

$$v_s(t) = -\frac{S_a}{w}[cos(wt) + \xi \cdot \sin(wt)] \cdot e^{-\xi wt} \tag{3}$$

According to the contents sliding mechanism described previously and shown in Figure 3, sliding initiates at a structural and contents acceleration of μg according to Equation 4. When the spectral acceleration of the structural response is less than μg, then no sliding occurs. Also, the contents velocity at that time of initiation and termination of sliding, $v_c(t_1)$ and $v_c(t_2)$, are the same as that of the structure, $v_s(t_1)$ and $v_s(t_2)$, given by Equation 5. where, t_1 and t_2 are the times of initiation and termination of sliding respectively.

$$a_s(t_1) = \mu g \tag{4}$$

$$\begin{aligned} v_c(t_1) = v_s(t_1) &= -\frac{S_a}{w}[cos(wt_1) + \xi \cdot \sin(wt_1)] \cdot e^{-\xi wt_1} \\ v_c(t_2) = v_s(t_2) &= -\frac{S_a}{w}[cos(wt_2) + \xi \cdot \sin(wt_2)] \cdot e^{-\xi wt_2} \end{aligned} \tag{5}$$

From Equations 1 and 4, the time of sliding initiation, t_1, is the solution of Equation 6:

$$\mu g = S_a \cdot sin(wt_1) \cdot e^{-\xi wt_1} \tag{6}$$

After sliding has been initiated, contents move with a constant total acceleration (μg). The contents relative velocity during sliding any time t between t_1 and t_2 is therefore given by the linear equation in Equation 7.

$$v_c(t) = v_c(t_1) + \mu g(t - t_1) \tag{7}$$

From Equations 5 and 7, the time of sliding termination, t_2, can be calculated using Equation 8. This does not have a simple explicit solution but can be solved numerically.

$$\begin{aligned} & -\frac{S_a}{w}[cos(wt_2) + \xi \cdot \sin{(wt_2)}] \cdot e^{-\xi w t_2} \\ & = -\frac{S_a}{w}[cos(wt_1) + \xi \cdot \sin{(wt_1)}] \cdot e^{-\xi w t_1} + \mu g(t_2 - t_1) \end{aligned} \tag{8}$$

The amount of contents sliding movement during the first excursion of sliding, Δ_{sfe}, may be determined by integrating the difference between structure and contents velocities from time t_1 to t_2 (i.e. the shaded area in Figure 3b) according to Equation 9.

$$\begin{aligned} \Delta_{sfe} &= \int_{t_1}^{t_2} [v_s(t) - v_c(t)]\, dt \\ &= \int_{t_1}^{t_2} \left\{ \left[-\frac{S_a}{w}[cos(wt) + \xi \sin{(wt)}] \cdot e^{-\xi w t} \right] \right. \\ & \qquad \left. - \left[-\frac{S_a}{w}[cos(wt_1) + \xi \sin{(wt_1)}] \cdot e^{-\xi w t_1} + \mu g(t - t_1) \right] \right\} dt \\ &= \frac{S_a}{w^2} \left\{ [2\xi \sin(wt_2) - \sin(wt_2)] \cdot e^{-\xi w t_2} \right. \\ & \qquad + \{\sin(wt_1) - 2\xi \cdot \cos(wt_1) + w(t_2 - t_1)[\cos(wt_1) + \xi \sin(wt_1)]\} \cdot e^{-\xi w t_1} \\ & \qquad \left. - \frac{\mu g \cdot w^2}{2S_a}(t_2 - t_1)^2 \right\} \end{aligned} \tag{9}$$

The content's first excursion sliding movement, Δ_{sfe}, due to a pulse excitation is a function of the coefficient of friction, μ, the structural characteristics (i.e. w and ξ) and spectral acceleration (S_a). A dimensionless contents movement factor, CNFESD (Contents Normalised First Excursion Sliding Displacement), equal to the first excursion contents movement, Δ_{sfe}, divided by the spectral displacement, S_a/w^2, of the structural response may be found from Equation 9 in Equation 10. Note that the dimensionless expression is similar to one presented by Newmark (1965), Yegian et al (1991), and Gazetas et al. (2009), but with explicit relationship among sliding demand, structural characteristics and subject loading.

$$\begin{aligned} CNFESD &= \frac{\Delta_{sfe}}{\left({}^{S_a}/_{w^2} \right)} \\ &= [2\xi \sin(wt_2) - \sin(wt_2)] \cdot e^{-\xi w t_2} \\ & + \{\sin(wt_1) - 2\xi \cdot \cos(wt_1) + w(t_2 - t_1)[\cos(wt_1) + \xi \sin(wt_1)]\} \cdot e^{-\xi w t_1} \\ & - \frac{\mu g \cdot w^2}{2S_a}(t_2 - t_1)^2 \end{aligned} \tag{10}$$

3.2 **Effect of Subsequent Sliding Excursions on Total Sliding Response**

For contents that may fall off a stand, off a table or off a shelf, the total sliding, CNSD (Contents Normalised Sliding Displacement), rather than the sliding in the initial excursion (CNFESD) is important. This is more difficult to estimate with simple equations, so the results of time history analysis are compared with first excursion sliding displacement so that the difference may be seen.

Effects of impulse magnitude and structural period on the total sliding, for structures with 5% damping and various periods (e.g. 0.5, 1.0, and 2.0 seconds) when subject to different impulse loading (I = 0.063, 0.125, 0.25, and 0.375g.s) were investigated. As shown in Figure 4, the total sliding (i.e. CNSD) was again independent of impulse magnitude and structural period. When compared with the initial sliding demand (i.e. CNFESD), good agreement was found as $\mu g/S_a$ was greater than 0.35. However, significant discrepancy existed between CNSD and CNFESD when $\mu g/S_a$ was less than 0.35.

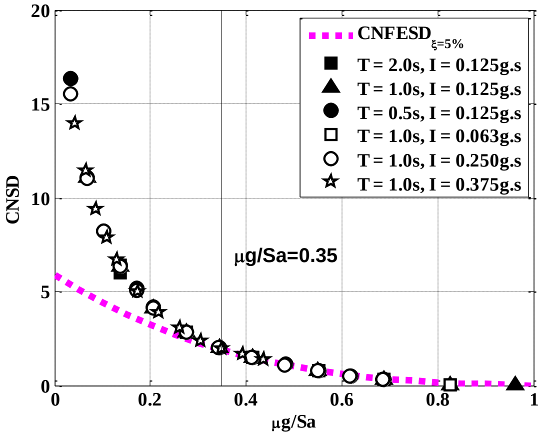
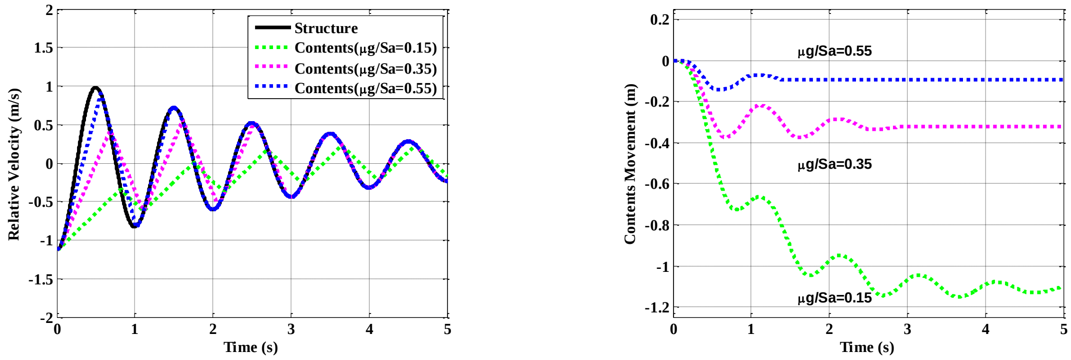


Figure 4. Contents movement, CNSD, for different normalised friction, $\mu g/S_a$,and period, T, due to impulse loading

In order to explain the difference, Figure 5 shows some structure and contents velocity and movement histories for different friction conditions (i.e. $\mu g/S_a$ values). It can be seen that as $\mu g/S_a$ decreased, the contents movement increased due to the transient effect in the contents sliding behaviour. The content is said to be in a transient state when its velocity has not yet reached steady-state condition. In the steady-state condition, the contents do not have a change in displacement over a cycle of structural response. It can be seen that for structures with small $\mu g/S_a$ that the CNFESD does not capture the CNSD response as a result of increased displacements in sliding excursions after the first one.



(a) Acceleration history

(b) Velocity history

Figure 5. Transient effect in contents sliding behaviour (T = 1.0s, ζ = 5%)

4 EARTHQUAKE RECORD EFFECTS ON SLIDING RESPONSE

4.1 Contents Sliding Seismic Demand

The earthquake records used here were the 20 SAC suite LA 10in50 ground motion records (Somerville et al. 1997). For each record, the normalised sliding demand was calculated via time history analysis on a linear structure with various periods (e.g. 0.5, 1.0, and 2.0 seconds) and damping ratio equal to 5%, and for different surface condition (μ). Twenty different μ values were conducted for each record, therefore a total of 1200 analyses were conducted for these 20 records. It was assumed that the distribution of CNSD is lognormal. Using the median and dispersion of CNSD, the 16th percentile and the 84th percentile of CNSD were calculated. Figure 6 shows the distribution of the normalised sliding demand, CNSD.

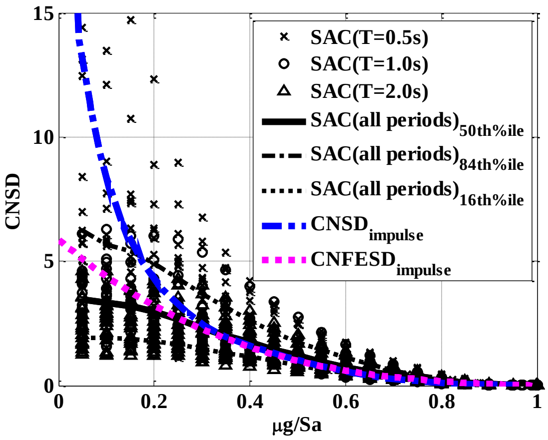


Figure 6. Contents movement when subject to earthquake loadings (T = 0.5, 1, and 2s, ξ = 5%)

Figure 6 shows that the sliding displacement was greater that the spectral displacement for $\mu g/S_a$ greater than about 0.5 (i.e. CNSD was greater than unity in this range). From observation, the relationship obtained from the impulse load analyses with 5% damping ratio for CNFESD, rather than CNSD, generally provides a better estimate of the median sliding movement of building contents during earthquake-type excitation. The earthquake-type ground motions show a significant variation in response and do not lie on one curve. This indicates that the characteristic of earthquake record, rather than just $\mu g/S_a$ is important.

Since the CNFESD can reasonably give the median sliding displacement for structures of all periods, and it will be more conservative if the damping ratio is assumed to be zero, the CNFESD can therefore be used to estimate the likely median sliding displacement for design.

4.2 Design Example

For an item of contents in a building which can be represented by a single storey structure like that used in this study, it is required to estimate the likely median sliding displacement for design. The spectral acceleration at the period of the structure is 0.9g and the friction factor between the contents and the floor is 0.2. The period of the structure is 0.7s. The structural damping ratio is 5%. The CNFESD is calculated from Equation 10. So CNFESD = 3.0 and Δ_{sfe} = 330mm. This is 3 times more than the structural spectral displacement of 110mm.

5 CONCLUSIONS

A study is described to quantify the sliding displacement demands of contents in an elastically responding single storey structure. It was shown that:

i) A simple mechanics-based method was used to determine the Contents Normalised First Excursion Sliding Displacement (CNFESD) on a structure subject to an impulse ground motion. An explicit approximation to obtain CNFESD as a function of the normalized friction coefficient, determined as the friction factor divided by the structural spectral displacement in terms of gravity, $\mu g/S_a$, was obtained. The CNFESD estimated the total response due to impulse well when $\mu g/S_a$ was greater than 0.35 but, for structures with $\mu g/S_a < 0.35$ subsequent sliding excursions also contributed to the total Contents Normalised Sliding Displacement (CNSD) as found from numerical integration. The CNSD as a function of $\mu g/S_a$ did not seem to depend on structural period of the structure or the magnitude of the impulse.

ii) For elastically responding SDOF structures the median CNSD from a suite of earthquake records was found to be generally similar to the CNFESD from impulse records with the same $\mu g/S_a$. The CNFESD may therefore be used to obtain a reasonable estimate of the likely sliding displacements in simple structures. A design example was provided.

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